Guemes Ferry Replacement: One Engineer's Perspective

Prepared for the consideration of:

- **Skagit County Commissioners**
- **Skagit County Public Works**
- **Guemes Island Ferry Committee**
- **People of Guemes Island**

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Revision History

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Executive Summary

Why is Skagit County trying to acquire a new electric ferry? The public continues to ask this question long after county officials have grown tired of answering it.[1] Members of the Guemes community sense that something is amiss, even if they struggle to define precisely what troubles them.

As a fourth-generation Guemes ferry rider and a licensed naval architect, I believe I have a duty to apply my specialized knowledge toward the reconciliation of community and county interests. To me it seems that we all share the same goals for the future of our ferry system: to minimize risk, cost, and environmental consequences.

<u>How can we be so divided over the path ahead when most of us agree on the goal?</u> I believe there are two causes. First, we disagree on the facts. Second, we have different visions of how the future will unfold.

<u>We disagree on the facts.</u> The county says that it wants to provide a "safe, reliable, and affordable ferry service" with "environmental benefits."[2] Few people would object to those goals. But county officials seem to have chosen a path that, according to their own naval architects, may not align with those goals. This document will show how the best available technical information suggests that, relative to a "baseline" geared diesel ferry,[3] an electric Guemes ferry is:

- Less reliable, with less capability in abnormal situations (pages 7-16).
- More expensive upfront and over its lifecycle, with greater cost uncertainty (pages 17-27).
- Less environmentally beneficial than other projects worthy of grants (pages 28-38).

<u>We have different visions of how the future will unfold.</u> Proponents of an electric ferry are optimists: they look forward, projecting today's trend of improvements in battery-electric vessels into tomorrow's status quo. Opponents of an electric ferry are pessimists: they look backward, assuming that battery-electric vessels have not fully outgrown their short and shaky track record. In the years to come, both of these viewpoints will be validated by newsworthy successes and failures.

As an engineer, I strive to be neither an optimist nor a pessimist. I strive to be a realist. To seek a realistic perspective on the electric ferry, I ask:

- How much would the optimistic future benefit us? Could we afford to miss that chance?
- How much would the pessimistic future harm us? Could we afford to take that chance?

In this document, I explain why we stand to gain little from the optimistic future, and why we are in a poor position to confront the pessimistic future. Because the pessimistic future hangs so heavily over our heads, I conclude that we would be best served by the most reliable and economical propulsion technology available today: diesel engines.

In preparing this document, I sought to complete three tasks:

1. **<u>To help us reach a consensus on the facts.</u>** Statements and beliefs about cost, reliability, and environmental benefit should be supported by official documentation.
2. **<u>To help recalibrate our vision of the future.</u>** A small public works department needs stable, reliable assets with minimal potential for failures and losses.
3. **<u>To help reconcile our interests.</u>** Skagit County and the public are best served by adhering to the county's formal goals and the findings of objective experts.

It takes some effort to complete these three tasks. **<u>If you do not have time to read the entire document, then I recommend either reading the introduction (pages 5-6) and the conclusion (pages 39-40), or reading just the headings and the bold underlined text.</u>**

Preface

Growing up with ties to Guemes, I was instinctually drawn to our special island community and the boats that putt around and toward it. I pursued rewarding careers in boat maintenance (1994-2000), boat construction (2001-2006), and boat design (2006-present). I earned a degree in naval architecture and marine engineering from Webb Institute, and I am a licensed professional engineer in those disciplines.

From 2011 to 2019, I worked for Glosten, the engineering firm designing our new ferry. Since 2016, my status as an employee of Glosten disqualified me from participating in public discourse related to the ferry. From 2016 to 2019, as Skagit County released several engineering studies and made several decisions related to ferry replacement, I became increasingly concerned about the dissonance between the engineers' findings and the county's decisions.

In 2019 I resigned from Glosten, moved home to Anacortes, and started my own engineering firm. Today, as an independent engineer, I am eligible to discuss my concerns with county officials and members of the Guemes community. Although I am speaking alone in this document, I personally know dozens of people in the Guemes community who are also concerned about the county's decisions. My goal is to validate their concerns through my engineering expertise.

This document is based on existing reports commissioned by Skagit County. I have woven in some facts from external sources, including some of my own calculations. **Everything cited in this document is either publicly available or reproduced with permission.** I invite readers to do their own research and synthesis, and to participate in this ongoing conversation.

As a piece of correspondence from a community member, this document cannot serve as a formal basis for Skagit County's decisions. I have neither the authority nor the resources to serve the county's engineering and planning needs. All I can do is draw attention to statements and expectations that do not seem to fit the facts presented by Skagit County and other reputable organizations. I have affixed my engineer's seal to this document upon the recommendation of the Board of Licensing,[4] because it contains some of the elements regulated by Washington Administrative Code (WAC) 196-27A-020.[5] I make these statements on behalf of myself only, in an effort to protect the best interests of the Guemes community, of Skagitonians, and of Skagit County's government.

This long document reflects my intention to catch up with the county's statements and decisions over the past four years. Yet as I reach out to Skagit County after this hiatus, I first seek to understand the county's present perspective on the ferry replacement process. To that end, **I would like to lead with these questions for county officials:**

1. What is your present plan for refitting or replacing the Guemes ferry?
    a. When will shipyard work begin?
    b. How will it be funded?
2. How did you choose this course of action?
    a. What were the criteria?
    b. Why was this choice superior?
    c. Which alternatives would be your second and third choices?
3. What obstacles could you envision encountering?
    a. How will you overcome them?
    b. What is your backup plan if you reach a dead end?
4. What is one thing you would change about the ferry replacement process?
5. What else should I understand about your perspective?

Introduction

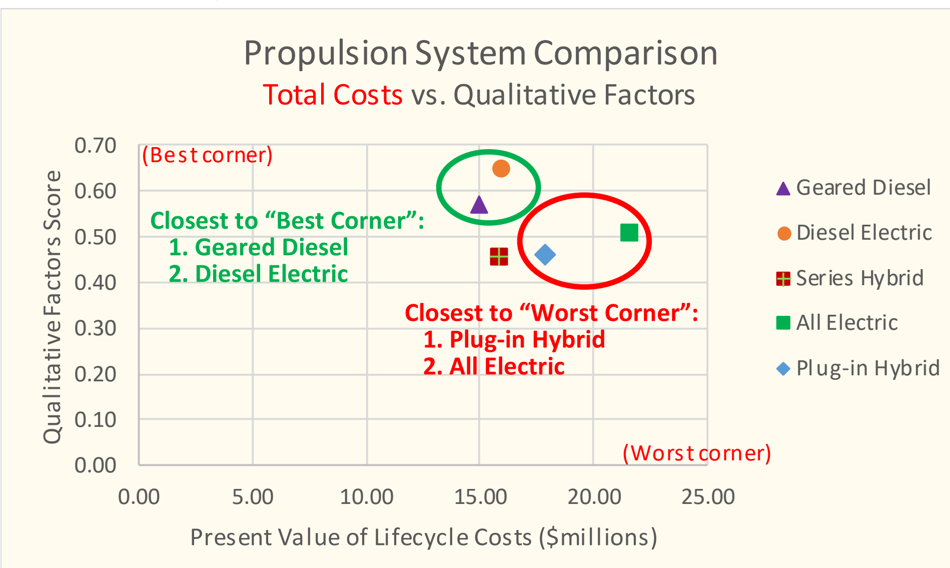
Key Ideas:

- Skagit County wanted an electric ferry prior to doing any analyses.
- Glosten conducted an impartial propulsion cost-benefit analysis, which concluded:
  - The best options are geared diesel and diesel electric.
  - The worst options are all-electric and plug-in hybrid.
- Skagit County is pursuing a fusion of the two worst options: all-electric and plug-in hybrid.
- Defying experts' advice puts Skagit County and Skagitonians at risk.
- The geared diesel ferry might be the only ferry Skagit County can afford.

When the commissioners signed Resolution R20150428 in late 2015, they believed an electric ferry could be "safe, reliable, and affordable," with "fiscal and environmental benefits."[2] Two years later, their engineering consultant (Glosten) released a thorough Concept Design Report (CDR)[6] that determined **an electric ferry is less reliable (CDR Table 28) and less affordable (CDR Figure 3) than a diesel ferry.** Rather than adapting to these facts, the commissioners continued to pursue an electric ferry as though nothing had changed. To my knowledge, nobody at the county has ever acknowledged any tension between their choice and their experts' conclusions.

The results of Glosten's study are best represented in Exhibit 1, which was created by county volunteer Jon Hodgdon.[7] The horizontal axis represents the total net present lifecycle cost of the propulsion system for the 32-car ferry—without grants, as none had been awarded at that time (Glosten CDR page A-2). (Skagit County downsized the design to 28 cars in 2019.[8]) The vertical axis represents the total propulsion system score, which was created jointly by Skagit County and Glosten. This score primarily measures reliability and environmental friendliness (Glosten CDR Table 28). **We could think of Exhibit 1 as a graphical cost-benefit analysis, with the "best" and "worst" corners labeled by Mr. Hodgdon.**

Exhibit 1. Hodgdon lifecycle cost-benefit plot with Glosten 32-car results, without grants



I added some circles and labels to Exhibit 1 to accentuate the results of Glosten's analysis. In the "best corner," where low cost meets high score, are the geared diesel and diesel electric options. **I would have expected a public agency, which is typically inclined to select the**

"lowest responsive and responsible bidder,"[9] to choose one of the "best" options. Instead, Skagit County chose the two options closest to the "worst corner," eventually settling on a fusion of those two options: "the all-electric concept with a back-up generator on board for emergencies."[10,11] Why would Skagit County make a 40-year commitment to the "worst corner?" **If the politicians and civil servants entrusted with our safety and economic security choose a path that opposes their experts' conclusions, then I would hope to see them provide a rational explanation for that choice.**

All of this information was publicly available when the commissioners, pressed by the County Road Administration Board (CRAB) to select a propulsion system for their grant application, chose the two systems in the "worst corner." County officials are quick to call this decision the point of no return.[11] Is the choice to electrify truly irreversible? It would be politically inconvenient in the short term. Yet I suspect CRAB members would want their grantees to succeed in the long term. **It seems logical to me that the CRAB would cooperate with a grantee who proposed a change that significantly reduced risk and cost.**

I also suspect that the CRAB members want the projects they support to get built. Presently we seem to be stalled out over a massive funding gap because we chose the project with the highest capital cost. If we were to choose a lower-cost alternative—namely geared diesel, which has the lowest capital cost—then we might have an easier time amassing the remaining funds. There was a time when we thought that the only way to afford a new ferry was to make it electric because of its potential to attract more grant money. **Given what we know today about the balance of costs and grants, a geared diesel ferry might be the only ferry Skagit County can afford.**

The other justification that I have heard for continuing to pursue the electric ferry is that it reduces Skagit County's operating costs relative to the geared diesel ferry.[12] According to this argument, somebody else will buy the electric ferry and its required infrastructure, and the savings in operating cost will print through to our fares. There are three problems with this justification:

1. Skagit County intentionally chose not to prioritize operating cost in its scoring system.[13] To say that operating cost is now the most important measure of merit is to discard all of the carefully thought-out effort that went into the scoring process in the first place.
2. Nobody has stepped forward to buy the ferry for us. With the grants we have today, Skagit County still loses almost two million dollars over the life of the all-electric ferry, relative to the geared diesel ferry. And even if a grant eventually does make up the cost difference, the all-electric ferry is still an inferior solution, according to the county's own scoring system.
3. The all-electric ferry has a higher chance of having expensive problems that could wipe out any forecasted post-grant cost savings relative to the geared diesel ferry.

Taken together, the all-electric ferry's high cost and low score reveal a deeper truth: it is difficult to electrify the Guemes ferry route. It is tempting to internalize these difficulties as a test of our devotion to the environment. Ironically, **our commitment to electrification is instead diverting attention and funding away from established, low-risk, low-cost programs that may be five to fifty times more effective at reducing carbon dioxide emissions.**[14]

In the following chapters, I will discuss the apparent dissonance between the county's stated goals and the county's choices. I have built this discussion around three principles that seem to guide our ferry acquisition process. I discerned these three principles by listening to the commissioners' statements at public meetings, by reading the county's publicly available documents related to ferry replacement, and by reviewing the results of the county's ferry polls:

Principle 1: Minimizing risk is our #1 priority.
Principle 2: Minimizing cost is our #2 priority.
Principle 3: We are still environmentalists.

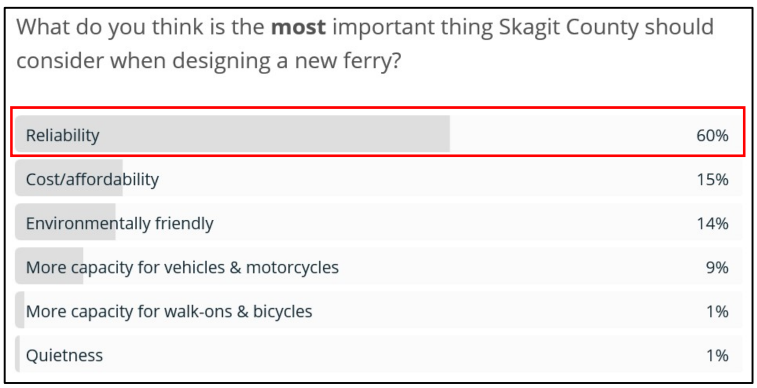
Principle 1: Minimizing risk is our #1 priority.

Key Ideas:

- 60% of county poll respondents said reliability is the most important design priority.
- 65% of the county's total propulsion system score is based on risk reduction.
- Glosten's reliability scores indicate that electric vessels are much riskier than diesel vessels.
- These risks affect performance and cost, from construction through lifelong operation.
- Relative to geared diesel, the all-electric ferry is:
  - More complex.
  - Technologically unstable.
  - Full of uncertainties.
  - Marginally functional.
- The early adopters of electric and hybrid vessels can afford more risk than we can.

The most widely agreed-upon aspect of the Guemes ferry replacement project is our attitude toward risk. In the county's first ferry replacement survey, an overwhelming **60% of respondents chose reliability as the single "most important" design consideration (Exhibit 2).**[15]

Exhibit 2. Design priority poll results, with emphasis on reliability

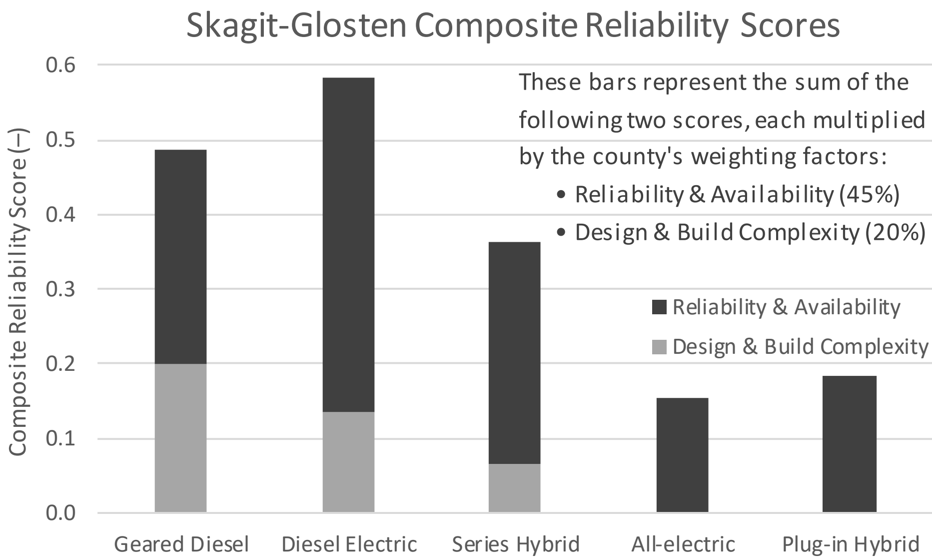


When Skagit County created its scoring system for propulsion options, it devoted 65% of the total score to risk reduction through two categories:[16]

- 45% "reliability and availability" measures the risk of "failures" and malfunctions, which affects how often the ferry is in service and on schedule. Higher scores mean lower risk, on a scale from 0 to 1.
- 20% "design and build complexity" measures the "risk to design and build" the ferry. I believe "design and build complexity" also has ongoing implications for maintenance and repair throughout the ferry's life. Higher scores mean lower risk, on a scale from 0 to 1.

I calculated a "composite reliability score" by adding Glosten's "reliability and availability" score to Glosten's "design and build complexity" score, using Skagit County's weighting factors for each score (CDR Tables 22 and 28). The sum of these scores represents the risk-based portion of the total propulsion system score (recall Exhibit 1). Composite reliability scores are presented in Exhibit 3, with the two contributing scores in different shades. A high score means high reliability and low risk. The "complexity" score does not appear for the all-electric and plug-in hybrid propulsion systems because Glosten gave them each a score of zero.

Exhibit 3. Skagit-Glosten composite reliability scores for propulsion system options



Even though Skagit County and the public agreed that "reliability" was by far the most important factor in replacing our ferry, county officials chose to pursue the two options with the lowest composite reliability scores. The option that was closest to the "best corner," the geared diesel system, has a composite reliability score that is respectively 3.2 and 2.6 times higher than the all-electric and plug-in hybrid systems' scores. **If everybody agrees that reducing risk is our top priority, then why did Skagit County choose the two riskiest options?**

Why are the all-electric and plug-in hybrid vessels' composite reliability scores so much lower? There are four major risk factors that I will suggest in turn, after briefly defining risk.

Defining Risk

Risk has two components:

1. The **probability** of an undesirable event occurring.
2. The **consequence** of an undesirable event occurring.

Decision-makers sometimes create a risk matrix to classify how the various combinations of probabilities and consequences might affect their operation. Glosten uses a risk matrix in the CDR as the basis for the "reliability and availability" score (CDR Table 25).

A fire in a machinery room is a common type of shipboard fire. The difference between diesel and electric vessels offers an instructive example of how both the probability and the consequence of a machinery fire can lead to substantially different levels of overall risk:

- On a diesel-powered boat, machinery fires tend to occur when fuel lines break. The probability of a fuel line failure is reduced by frequent inspection and maintenance of the fuel system. The consequence of a fuel line failure is limited by external fuel shutoffs and fixed fire suppression systems that extinguish hydrocarbon fires rapidly and effectively.
- On a battery-powered boat, machinery fires tend to occur when batteries enter thermal runaway. The causes of these failures tend to be invisible before the incident, and to remain unknown until after an investigation, making them difficult to prevent and detect until it is too late to stop the chain reaction. The consequence of thermal runaway can be disastrous, because we do not yet have the technology to extinguish lithium battery fires quickly.[17]

Risk Factor 1: High Complexity

Consider the differences between Glosten's propulsion system schematics for the geared diesel ferry (Exhibit 4) and the plug-in hybrid ferry (Exhibit 5).[18] I have chosen the plug-in hybrid ferry as the point of comparison for system complexity, because the all-electric ferry in the CDR did not have a backup generator onboard. Now that the all-electric ferry has a backup generator onboard, I believe that the diagrams of the plug-in hybrid ferry may better represent the propulsion system that the county intends to pursue.

Exhibit 4. Propulsion system diagram, geared diesel system (CDR, one end)

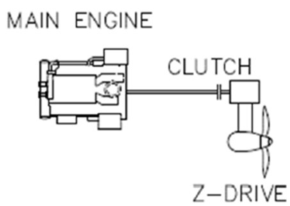
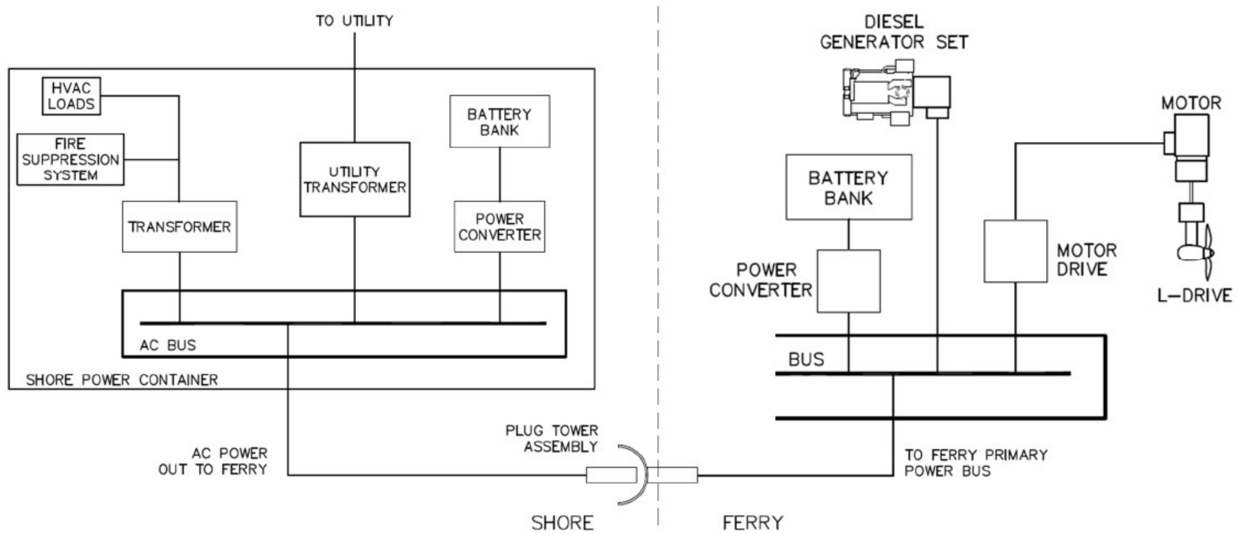


Exhibit 5. Charging & propulsion system diagrams, plug-in hybrid system (CDR, one end)



The geared diesel system relies on two major components, whereas the plug-in hybrid system relies on ten major components, plus a battery management computer that is not shown. **All of the components in Exhibit 4 and Exhibit 5 must be engineered to work with one another, which can become difficult as the number of components and vendors increases.** The greater number of components also creates a greater number of independent failure points.

All of the shipboard components must be working normally in order for the ferry to be in service. Redundancies allow the ferry to get back to the dock, but the Coast Guard does not allow the ferry to continue operating on its backup systems—because if the backup systems fail, then the vessel is helpless.[19]

Risk Factor 2: Technological Instability

Electric vessel technology, and battery technology in particular, is rapidly evolving right now. Although this evolution allows us to dream of new applications, it also makes today's technology unstable. This instability harms early adopters in two ways:

1. **Instant obsolescence**, by which better and cheaper components keep replacing last year's better and cheaper components. **It is difficult to design, build, maintain, and repair a ship when the parts and their specifications keep changing.** Supply issues could lead to delays or imperfect substitutions. The corporate landscape is also evolving rapidly, which may lead to mergers and closures that end the production of parts on which we rely.
2. **Performance variability**, by which components that are assumed to be similar or identical do not behave similarly or identically. New battery models are brought to market so quickly, and battery cells are sourced so erratically, that quality control remains a real concern.[20] Marine battery performance predictions are based on such scant real-world data that **some users are bound to be surprised by underperformance, recalls, and failures.** Because the margins are already so slim (as Risk Factor 4 explains on the following pages), batteries and charging systems do not have to be much less than perfect to disrupt ferry operations. Chronic underperformance issues force operators to choose between offering a lower-than-expected standard of service or making "upgrades" to meet their original expectations.

Risk Factor 3: High Uncertainty

Because so few modern electric ships have existed for so short a time, the world has no statistically significant data on their reliability and cost. After millions of lifecycles over the past century, the world has good numbers for the reliability and cost associated with modern diesel boats, and a good idea how to minimize failures. This means that we cannot calculate the reliability or cost of an electric ferry with as much certainty as we can calculate the reliability or cost of a diesel ferry. **This lack of certainty exposes today's electric ferry owners to a broader range of outcomes, and thus to greater risk, even if the averages look acceptable.**

Averages do, however, help the operators of large fleets. The combined outcomes of many vessels, with a variety of new and old propulsion technologies, gives them operational and financial stability—just as the average of many coin tosses is 50/50, according to the law of large numbers. But **when we have only one boat, we cannot be helped by the law of large numbers**—just as possession of the ball in some sports is decided by a single coin toss.

An article contributed to the January 2019 ferry newsletter highlighted several electric and hybrid vessels around the world.[21] From that article, we might be tempted to conclude that electric ship propulsion has become a mainstream option. Such generalized comparisons mask the relative levels of risk accepted by the early adopters of electric vessels. These early adopters are only slightly increasing their total risk exposure, as we can see in Exhibit 6, where I have contrasted the proposed Guemes route with three other passenger routes mentioned in that article.

With the exception of Skagit County, all of the organizations in Exhibit 6 have sizable revenues and fleets, which means they can endure the financial and operational penalties of owning a "lemon." With the exception of Skagit County, all of the organizations have assigned at least three boats to the electric vessel's route, including at least one "baseline" diesel boat, to provide high redundancy. With the exception of Guemes, all of the destinations can be reached without a ferry, lessening the consequence of service disruptions. And with the exception of Guemes, all of the destinations in Exhibit 6 have road access to hospitals, lessening the health risk posed by failures and outages. Skagit County has none of these crucial redundancies. **For the early adopters, one disabled boat is an inconvenience. For Skagit County, one disabled boat is a crisis.**

The early adopters in Exhibit 6 have used electrification as a strategy to diversify their fleets. They are taking a risk on new technology in ways that only slightly increase their total risk exposure. With only one boat and a high sensitivity to cost fluctuations,[22] Skagit County seems poorly positioned to gamble at these tables.

Exhibit 6. Comparison of proposed and active electric and hybrid passenger vessels

Route	Guemes	Bainbridge	San Fran. Bay	Lavik-Oppedal
Status	Proposed	Planned	In service	In service
Owner & operator	Skagit County	WA St. Ferries	Red & White	Norled / DSD
2018[A] fare revenue ($mn)[23]	**1**	195	Est. 10 - 22	286
Boats in fleet[24]	**1**	22	4	80
Total boats on route, of which:[25]	**1**	3	4	3
→ **Hybrid or all electric**	1	1/2[B]	1[C]	1
→ **Diesel or diesel electric**	**0**	2/1[B]	3	2
Miles by road[26]	**No road**	92	0 (tour)	42/195/583[D]
Road access to hospitals[27]	**No**	Yes	Yes	Yes

[A] Annual or fiscal year, as reported. Total fare revenue from all routes is provided above.
[B] The hybrid conversions will be done one at a time. Until ca. 2025, they will run exclusively on diesel fuel.
[C] This plug-in hybrid boat seems to run mostly on biodiesel.
[D] Two other ferry routes and one road route are available.

Risk Factor 4: Marginal Functionality

There are three main reasons why today's electric vessels are only marginally functional.

1. Electric vessels stress the electrical grid.

When our 28-car electric ferry plugs in to charge at the Anacortes dock, it draws as much power as roughly 1,300 homes do.[28] The electrical grid cannot handle that kind of sudden variation in loading. To smooth out the variations, Skagit County intends to build a secondary battery system onshore, as many operators of electric vessels have done.[29] **This additional equipment increases failure potential, decreases efficiency, and adds a great deal of cost to the project.** Even with the battery smoothing the load on the grid, the electric ferry's power demand is still so high—equivalent to roughly 380 homes—that the local wiring must be upgraded at an additional cost.[28]

2. Charging an electric vessel is complicated.

Every time the electric ferry docks in Anacortes, it needs to connect immediately to the charging system, and it needs to remain connected until just before departure.[30] Skagit County chose to automate the task of connecting and disconnecting the charger, because a manual connection would have taken too much of the crew's time.[31] Automatic charging connections are new, expensive, complicated, and sensitive to vessel motions. The operators of Norled *Ampere* had to purchase additional equipment so that their laser-guided automatic charging connection would work:

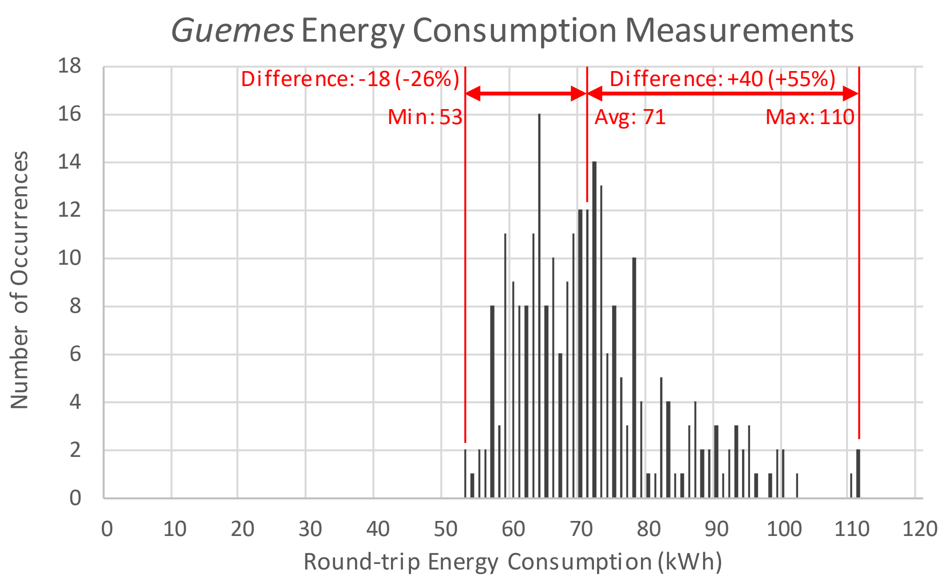
> **The electric ferry has to be kept completely steady while at the quayside in order to plug it in. To make this possible, we developed a unique automated docking system.[32]**

Norled's experience indicates that **weather conditions may restrict the electric Guemes ferry's ability to charge,** especially if an automated docking system is not installed. Glosten acknowledges that an automated docking system may be "required for vessel motions during automatic charging," but it has not included the cost of such a system in its cost estimates. The mechanical components alone cost $600k, and they require foundations over the water.[33]

Full and frequent charging is crucial to battery longevity. Our all-electric ferry is intended to be fully recharged after every round trip, which uses only the top 20% of the battery's charge on average. If we regularly use the top 30% of the battery's charge instead, then the battery's lifespan will be cut in half.[34] This is why the ferry must not often depart before the battery is fully charged.

Although the "average" round trip is expected to deplete only the top 20% of the battery, the actual battery depletion on each round trip is a function of the energy consumed on that trip. Energy consumption is influenced by many factors, including the weight of vehicles carried, weather conditions, and the time the ferry spends holding itself against the dock. Exhibit 7 shows the range of energy consumed by *Guemes*'s engines on round trips during an 11-day study in the spring of 2016.[35] The horizontal axis shows the range of energy consumption, and the vertical axis shows the number of times each value occurred. From this brief study during unremarkable weather conditions, we already see that, **relative to the average energy consumption, the extreme values spread out twice as far to the right (high consumption) as they do to the left (low consumption).**

Exhibit 7. Energy consumption measurements from *Guemes*



Given the potential for the ferry to consume much more energy than average, and the importance of recharging the battery to 100% each time before leaving the dock, the size of the charging system is crucial. The bigger the system, the faster the ferry recharges—and the more money we must spend to avoid stressing the power grid.[36] Some of the required technology is still under development: the 32-car electric ferry in the CDR had a charging connection that theoretically allowed on-time departures 95% of the time, but that theoretical connection was twice as big as any connection available at the time.[37] Out of technical and financial necessity, Glosten reduced the size of the 28-car ferry's charging connection by 62% relative to its original size.[38] This reduced connection size means that **the charging system is now less capable, which reduces the capability of the electric ferry:**

During days of above normal currents or high wind and wave events, combined with full loads of vehicles, the charging system will restrict the vessel's schedule to less than 2 round trips per hour.[39]

Heavy loads and inclement weather could increase the crossing and loading/unloading times for any of our ferry options, causing them to fall behind schedule. But only the electric ferry would fall even further behind schedule because of its need to charge. This is one example of how **an electric ferry's limitations amplify the operational challenges that we face in abnormal situations.**

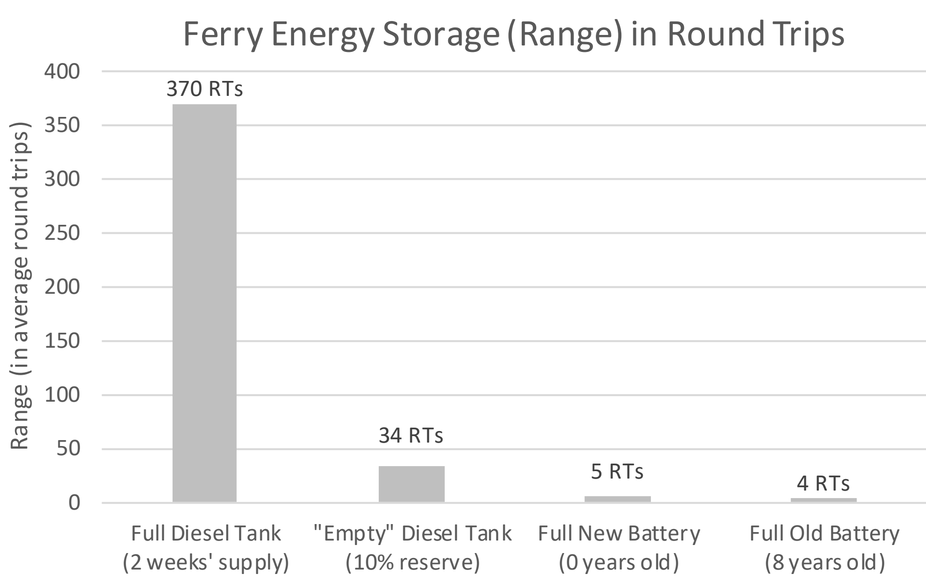
Many of us might agree that the occasional inconvenience of waiting for a full charge is a small price to pay for saving the planet. Yet there may be some situations in which forced charging time could pose a risk to life and property.

3. Electric vessels cannot store much energy.

Per unit of stored energy, today's state-of-the-art marine battery bank is 100 times heavier than diesel fuel, and it is 5,000 times more expensive than a diesel tank.[40,41] Because ships are weight-sensitive—and their owners are cost-sensitive—the viability of electric vessels relies on making the battery bank as small as possible. This is why today's electric vessels run short routes and charge frequently.

Naval architects use the term **range** to describe the distance a ship can travel without refueling. Exhibit 8 illustrates how the limitations of today's battery technology affect the Guemes ferry's range. The vertical axis shows the ferry's range in terms of average round trips. The diesel concept design holds enough energy for two weeks (roughly 340 round trips), plus 10% reserve (roughly 34 round trips), for a total of roughly 370 round trips.[42] When the tank is nominally empty and only the 10% fuel reserve remains, the diesel ferry still has more than enough energy to run all day (on average, the ferry makes 24 round trips per day).[43] The electric concept design holds enough energy for just five round trips when it has a new, fully charged battery. As the battery ages in service, its capacity is likely to drop by a few percent each year, making the margins even slimmer over time.[44] When the battery is eight years old and nearing replacement, it might only hold enough energy for four round trips when fully charged.[45] **A diesel ferry with an empty fuel tank has six to eight times the range of an electric ferry with a full battery.**[46]

Exhibit 8. Ranges of diesel and electric concept designs



With so little range, electric vessels are at risk of becoming incapacitated if they cannot charge regularly and fully.[47] To reduce this risk, **most so-called "all electric" ships have at least one diesel backup generator onboard.** The backup generator is used to power the vessel whenever grid power is inaccessible for any reason, or when the batteries cannot support vessel operations.[48] Although a backup generator is essential in these situations, it is a burden the rest of the time. Backup generators and their auxiliary systems are heavy and expensive. The designer's challenge is to strike a balance between safety and cost when sizing the backup generator(s).

The original all-electric Guemes ferry design had no backup generator aboard. The revised all-electric Guemes ferry design has one backup generator aboard, but it is not powerful enough to make the electric ferry as capable as a diesel ferry is in abnormal situations, as a county official explains:

The vessel will be able to operate at a reduced tempo and capability with only the backup generator running.[49]

Although I await a more detailed explanation from the county,[50] it appears that the electric ferry may be incapable of operating for several hours at high power levels. If so, then **the electric ferry would be less capable in abnormal situations than a diesel ferry would be.** Although this unusually long range would only be tested on rare occasions, those rare occasions may be the ones when we need the ferry most.

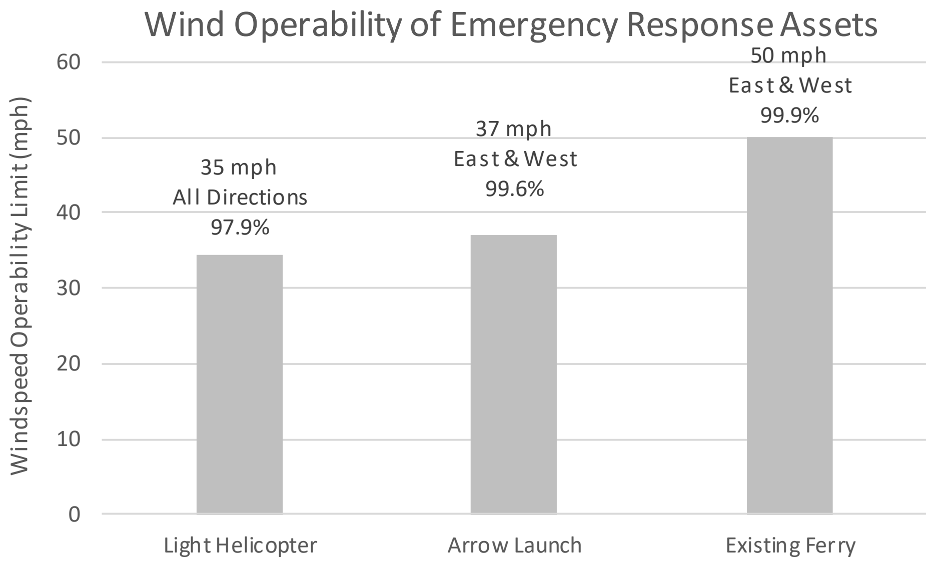
In severe weather, energy consumption can increase dramatically as the ferry battles wind, waves, and current. The normal ferry route puts these environmental forces on the beam of the ship, which can push it off course and cause violent rolling.[51] To ease these problems, the captain sometimes keeps one end pointed into the waves throughout the crossing, which could double the route length and further increase energy consumption. On a recent stormy day, we saw *Guemes* operating east of Cap Sante, on a voyage that must have been more than twice the length of a normal crossing (Exhibit 9).[52] **The backup generator would improve the electric ferry's range, but would it be enough to sustain the ferry through these extraordinary situations?** Would it be sufficient for all of the situations the new ferry might encounter over its lifetime?

Exhibit 9. Northeast-looking view showing *Guemes* operating east of Cap Sante

It is fair to ask why the ferry would leave the dock in such bad weather. I do not know all of the reasons, but I can think of at least one reason: it might be the only way off the island. Exhibit 10 shows the windspeed operability limits (vertical axis) for three ways of getting from Guemes to the hospital: a light helicopter (e.g. Airlift Northwest), a small boat (e.g. Arrow Launch Service), and the Guemes ferry. The first emergency response asset to be grounded in high winds is the helicopter (35 mph from any direction, per interagency guidelines).[53] Easterly or westerly winds above 37 mph have historically made conditions too rough for an Arrow launch to land at the Guemes dock. The existing Guemes ferry has served in easterly or westerly winds as high as 50 mph.[54]

Exhibit 10 also states the likelihood of these wind conditions—which, it should be noted, can have different impacts on operability depending on the current. High winds are uncommon; a ferry with unlimited range only slightly increases our ability to respond to emergencies in bad weather. But it does increase them. And since our ferry is the default means of crossing Guemes Channel, it probably has the lowest risk, lowest cost, and highest readiness of any asset available to respond, regardless of weather conditions. For these reasons, I suggest that **<u>a Guemes ferry with a long range fills an irreplaceable role in Skagit County's emergency response network.</u>**

Exhibit 10. Estimated wind operability limits of emergency response assets



<u>The Guemes ferry is most valuable as an emergency response asset in the worst weather, when all other assets are unavailable.</u> This is why I believe that the ferry should be able to operate for long stretches of time at full power levels, so that there would be no doubts regarding its ability to serve any of the functions listed below without limitations on its range:[55]

- Crossing Guemes Channel in heavy weather as the emergency vehicle of last resort.
- Holding on the Guemes side during an emergency for a long time, regardless of weather.
- Serving an emergency that requires several fast round trips, regardless of weather.
- Rendering assistance on the water for an extended period of time, regardless of weather.
- Serving emergency needs during a major storm and a power outage, which tend to coincide.

These are just a few examples based on our recent experiences and limited imaginations. The future may hold surprises that we could not envision today. The Concept Design Report warned us about the marginal functionality of the electric ferry in emergency situations:

> **The existing vessel is capable of providing a variety of response scenarios, and it is assumed that the replacement vessel must also be able to do so. The all-electric and plug-in hybrid propulsion systems make this requirement difficult to meet.[56]**

Long range is an inherent characteristic of a diesel ferry. **<u>With an electric ferry, we must pay a high premium for range, so we only want to pay for as much range as we need.</u>** How much range do we need? There is no way to know for sure until the end of the ferry's life. Underestimating it now would be a liability. Overestimating it now would be a waste of money.

<u>Today there is no cost-effective way to have an electric Guemes ferry that is anything other than marginally functional.</u> If Skagit County insists upon owning a marginally functional emergency response asset, then it might do well to develop secondary transportation procedures for heavy weather. Given how low the all-electric ferry's composite reliability score is, Skagit County may need this backup plan regardless of weather concerns.

Many islands around us have no dedicated ferry service and no medical facilities. The people who live on those islands have accepted additional risk and uncertainty in exchange for other aspects of a fulfilling life. So too could it be for Guemes: **as a community, we could choose a less reliable, less available ferry in exchange for the perceived benefits of electrification.** If this were the county's strategy, then I would hope to see the matter put to an advisory vote, preceded by a practical explanation of the compromises. Glosten observed that the Guemes community's expectations for emergency services are based on the performance of the existing diesel ferry:

> **The existing Guemes Island ferry has set a standard of emergency response for the community.**[57]

The Paradox of New Technology

Today we face the classic paradox of any promising new technology: **it only becomes affordable and reliable when it is widely adopted, and it only becomes widely adopted when it is affordable and reliable.** Today's best commercially available battery technology is only good enough to support an extremely limited range of marine propulsion applications, which means that rapid innovation is likely to continue. Tomorrow's best battery technology will be better than today's, but it will still be expensive and unstable. Today's best battery technology, if it withstands the test of time, will become cheaper and more stable tomorrow. This is a difficult time for a vessel owner to bet on batteries, even if their future prominence seems assured.[58]

In just the past five years, electric ships have become icons of human ingenuity, long before their technical merits can be proven decisively in real-world applications. Norled *Ampere* won a "Ship of the Year" award eight months before its maiden voyage.[59] In late 2017, the Washington State Department of Commerce launched the Maritime Blue 2050 Initiative. Its goal is:

> **…to bolster innovations in the maritime sector that create living-wage jobs, protect the environment and ensure sustainability for the industry. Imagine ships and passenger ferries powered by electricity…**[60]

Electric ships are gaining repute as a technological panacea that could save our environment and stimulate our economy. Yet **new technology sometimes falls short of our expectations, and it seldom makes a flawless debut.** If you look beyond the hopeful headlines, you can find evidence in the public record that the sailing has not always been smooth for early adopters of electric vessels:

- 2012: The hybrid tug *Campbell Foss* suffered a major battery fire, which was later determined to have been caused by a software issue.[61] After three months of repairs, it returned to service running on diesel only, with plans to install a redesigned battery system in a year.[62]
- 2015: "Some initial kinks made [Norled *Ampere*] lag the two other ferries that travel the same route."[63]
- 2018: The conversion of *Gees Bend*, the first all-electric vehicle ferry in the United States, was expected to take 3.5 months.[64] It was 14 months before the ferry returned to service.[65]
- 2019: Batteries aboard the Norled ferry *Ytterøyningen* caught fire and exploded. The cause is unknown and under investigation.[66] The batteries were installed in 2018 as part of a diesel-hybrid conversion.[67] Damage is estimated at $2.2mn, and repairs will keep the ferry out of service for "some months."[68]

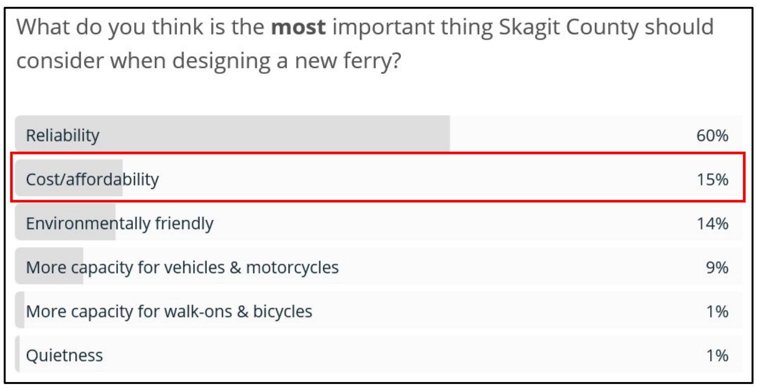
Principle 2: Minimizing cost is our #2 priority.

Key Ideas:

- We need to answer four questions about the cost of an electric ferry:
  - What is our budget? (We need a budget.)
  - Can we afford to pay more upfront? (We might not be able to afford it.)
  - Does it save more money than it costs? (Electric never breaks even with diesel.)
  - How reliable are the cost estimates? (Diesel's cost estimates are more reliable.)
- Refitting the existing ferry could be part of the lowest-cost acquisition strategy.
- Grants can be a means of compensating early adopters for taking a risk.

Returning to the design priority poll (Exhibit 11), **the community's second-highest priority was "cost and affordability," with 15% of the vote,** just behind being "environmentally friendly" (14%).[15]

Exhibit 11. Design priority poll results, with emphasis on cost



For county officials, minimizing cost seems to be no less important than the #2 priority, because the whole reason the county wants to build a new ferry is to "minimize the overall cost of ownership" (i.e. lifecycle cost).[69] Moreover, when the commissioners chose to pursue electric propulsion technology, they seemed focused on this new technology's ability to expand "the potential funding options," whereas "environmental benefits" were just a bonus.[2] The importance of cost is reinforced in the cost-benefit plots made by Glosten (see Figures 4 and 5 in the CDR) and Jon Hodgdon (Exhibit 1), where cost gets its own axis.

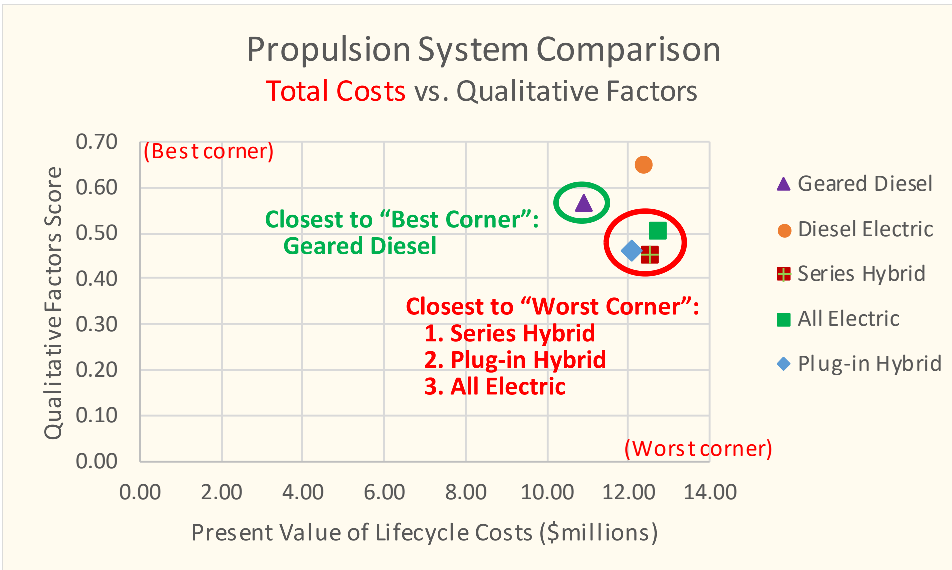
In 2015 and 2016, two separate vendors presented the concept of electrification to the commissioners as a cost-saving measure. They said that the electric ferry would cost more upfront than a diesel ferry would, but that its lifecycle cost would be lower.[70] In this chapter, I will ask and answer four questions to evaluate that proposition. Before we begin, I will update our cost estimates to represent the 28-car ferry instead of the 32-car ferry. The costs in this chapter are presented in late 2017 dollars, to maintain consistency with the majority of cost estimates released by Glosten.

Estimating 28-car Ferry and Propulsion System Costs

After the county downsized from the 32-car ferry design to the 28-car ferry design, it only updated its cost estimates for the all-electric variant. There are no formal cost estimates for the other variants, so I scaled them using publicly available information, as described in Appendix A. The county would need to produce its own formal cost estimates if it wished to follow up on my conclusions.

Exhibit 12 provides an updated Hodgdon cost-benefit plot for the 28-car ferry. The horizontal axis contains estimated 28-car propulsion system lifecycle costs, including both propulsion-specific grants that we have secured, as they apply to each option.[71] I have not applied the CRAB grant toward the cost of propulsion systems, because the grant announcement contains no stipulations about propulsion technology, so it does not affect this cost comparison.[72] The vertical axis contains the total Skagit-Glosten propulsion score from the CDR (CDR Table 28). We see that the trend has not changed: **even after accounting for all of the propulsion-specific grants we have today, the geared diesel system is still closest to the "best corner," and the electric and hybrid systems are still closest to the "worst corner."** For less than it would cost to own and operate the all-electric ferry, we could own and operate the diesel-electric ferry, which has the highest rating of all options considered.

Exhibit 12. Hodgdon lifecycle cost-benefit plot with estimated 28-car results, with grants



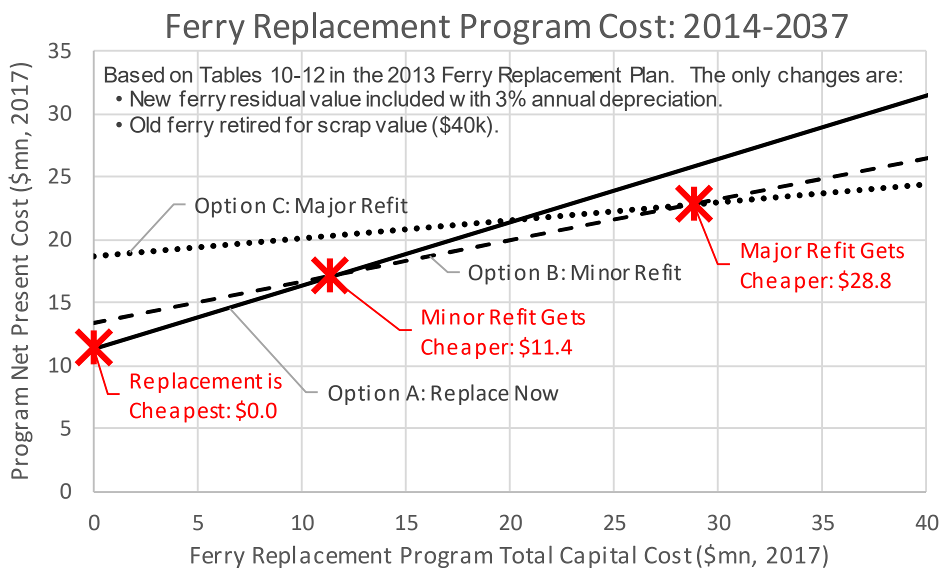
Question 1: What is our budget?

Cost often sends important signals about the practicality of an idea. When the sky is the limit, it is easy to get hung up on a suboptimal solution and to ignore better, lower-cost alternatives. We have become so fixated on a new electric ferry, and on the grants it might attract, that we have never publicly discussed an upper limit on cost. **There must be some price above which electric propulsion—or even a new ferry—no longer makes sense financially.**

I began thinking about this problem in earnest when cost estimates came out for the 32-car ferry in late 2017. The 28- and 32-car electric ferries cost respectively two and three times as much as we thought a new ferry would cost when our experts recommended immediate replacement in the Ferry Replacement Plan.[73] Does this price shock change the Replacement Plan's conclusion that immediate replacement is the lowest-cost option?

It absolutely does. Exhibit 13 shows the total program cost (vertical axis) of the three options in the Replacement Plan as a function of new vessel cost (horizontal axis).[74] The graph has crossover points at $11.4mn, where a minor refit becomes more cost-effective than building a new ferry, and at $28.8mn, where a major refit becomes more cost-effective than a minor refit. **According to Exhibit 13, our budget for immediate replacement should be $11.4mn.** If the cost of a new ferry is greater than $11.4mn, then Exhibit 13 says we are better off postponing replacement.[75]

Exhibit 13. Ferry replacement program sensitivity to replacement ferry capital cost



How do grants influence this $11.4mn upper limit? The answer seems to depend on the structure of the grant. If the grant is awarded in a lump sum and it must be spent right away, then it could apply toward the cost of the new ferry. Yet our main grant—the CRAB grant—is structured very differently, in a way that might actually reinforce the case for postponing replacement when the new ferry's cost exceeds $11.4mn.

The CRAB grant pays out over 15-20 years, and it does not require grantees to make their capital investments upfront.[76] This means Skagit County could continue operating the existing ferry while the CRAB payments roll in. During this time, the replacement surcharge would also roll in.[77] When the post-refit ferry reaches the end of its life after 8 or 15 years,[78] Skagit County would have millions of dollars set aside for a new ferry, reducing the bond debt it would have to issue.

Appendix B explains how I created Exhibit 13 from available county documents, most notably the Replacement Plan. Because Skagit County's approach has changed so much since the Replacement Plan was issued, Exhibit 13 may no longer represent the costs of the county's options. This lack of updated guidance concerns me, because **Skagit county is using a report recommending a new $8.4mn diesel ferry as justification for buying a new $18.9mn electric ferry.**

After reviewing the Replacement Plan, I concluded that it could use updates to its methodology and its inputs in order to represent the situation in which Skagit County finds itself today. The summaries below are described in greater detail in Appendix B.

Replacement Plan: Methodology

Skagit County chose to deviate from an industry-standard lifecycle cost estimation methodology in two ways that may have biased the outcome in favor of immediate replacement.[79,80] I recommend revising the Replacement Plan's methodology as follows to conform to industry-standard accounting practices:

1. **Accounting for the time value of money.** Present dollars are considered more valuable than future dollars, because there are opportunity costs when funds are committed.[81] The CDR assumed a 3% annual **discount rate** for the time value of money. There are two reasons why the time value of money matters even more to Skagit County. First, Skagit County has just established a replacement fund that will earn roughly $600k per year between the CRAB grant and the surcharge.[82] The longer this fund is left to accrue, the less

Skagit County must pay in borrowing costs. Second, the cutting-edge electric equipment that Skagit County wants to buy is likely to become more affordable and reliable in the years ahead. The CDR assumed that batteries would get cheaper by 2% per year relative to all other vessel components.[81]

2. **Accounting for the age of the replacement ferry.** Newer ferries are capable of operating farther into the future, thereby postponing the next expensive refit or replacement. Because ferry replacement is a never-ending cycle, the age of the ferry at the end of each replacement scenario matters a great deal. The 18 years between Option A (replace now) and Option C (major refit now, replace later) could span half of the next ferry's lifetime. This difference can be accounted for in each scenario by assigning the ferry a **residual value** based on its age at the end of the analysis period. By not accounting for the age of the replacement ferry, Skagit County ignores all of the financial benefit that it gets out of refurbishing the existing ferry. I had to include residual value to create Exhibit 13, otherwise the three lines never would have intersected.

Replacement Plan: Inputs

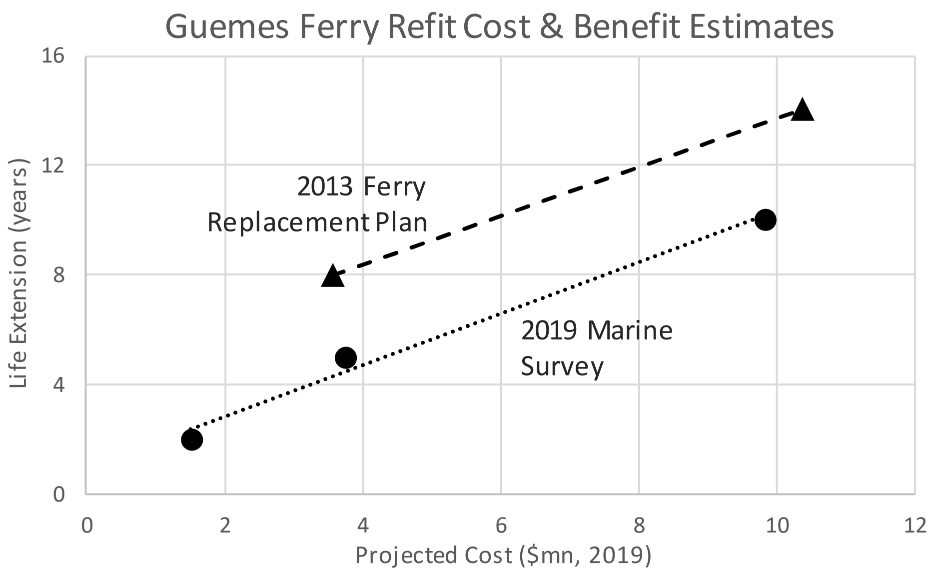
Skagit County has learned much about its ferry replacement options since the Replacement Plan was released in late 2013. Back then, the only ferry under consideration was a simple 26-car diesel ferry with an estimated capital cost of $8.4mn.[83] Skagit County is now interested in a more complex 28-car electric ferry with an estimated capital cost of $18.9mn.[71] The CDR has shown that the operating cost of an electric ferry could be lower than that of a diesel ferry.[84] **All of this new information could change the outcome of the Replacement Plan.** I recommend updating the Replacement Plan with these new inputs, and revising it as needed to ensure a consistent level of detail across the range of options. At a minimum, I recommend refreshing the three options that seem most economical or most likely to be chosen: the minor refit option, the baseline diesel option, and the all-electric option. A set of curves could be generated for each of the replacement options, similar to the set shown in Exhibit 13.

One of the most important factors in evaluating the two refit options is the length of time each refit allows us to postpone the purchase of a new ferry. As a part of updating the Replacement Plan, we should resolve a disagreement regarding post-refit longevity between the Replacement Plan and the latest marine survey.[85] Exhibit 14 illustrates how the relationship between the inflation-adjusted refit cost (horizontal axis) and the predicted length of life extension (vertical axis) are very different in these two documents. **The Replacement Plan consistently estimates four additional years of longevity for each of the refit actions,** which substantially affects the value extracted from our investment in a refit.[86]

There also seems to be widespread misuse or misunderstanding of the latest marine survey's comparison between "cost to cure" (i.e. refit cost) and fair market value. **We cannot simply say that the ferry should be discarded when its refit cost exceeds its fair market value.** What matters is the total net present program cost of the existing ferry relative to the total net present program cost of the alternatives, less revenues and residual values of assets, over some period of time.

If you drive an economy car from the mid-2000s or earlier, then your next five years of maintenance costs (assume $5k) could exceed the value of your car. Should you run out and buy a new car immediately (assume $20k) to save money? New cars need maintenance too, and soon they become old cars.

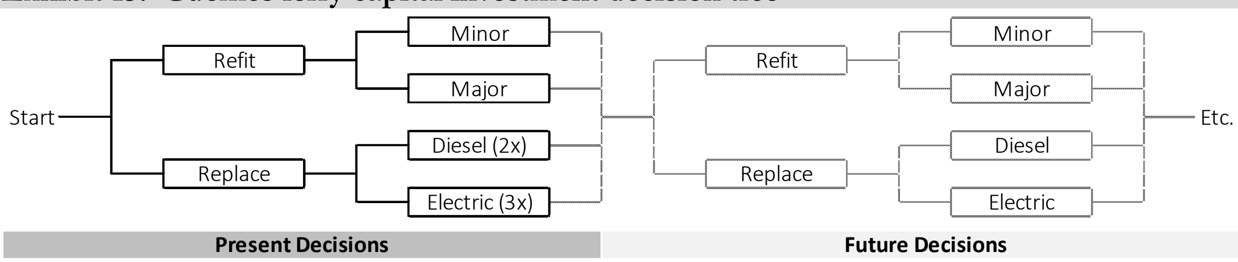
Exhibit 14. Comparison of ferry refit cost and life extension estimates



Final Thoughts on Budget

A budget provides a framework for decision-making. We know that we must make capital improvements to our ferry system in the near future.[87] Presently our decision tree (Exhibit 15) has three principal forks: refit or replace, minor or major refit, replace with diesel (two options) or electric/hybrid (three options). I included some decisions beyond those we must make today, to illustrate how this process is a never-ending cycle of choices. **Because the CRAB grant has a long payout period, the refit and replacement options need not be mutually exclusive.**

Exhibit 15. Guemes ferry capital investment decision tree



If the goal is to "minimize the overall cost of ownership"[69] in the foreseeable future, then Skagit County could recalculate the lifecycle cost of each option on the decision tree, and then follow the tree to the lowest-cost solution. Given the Replacement Plan's great potential to be revised, and the strong evidence that electrification is not the lowest-cost option (even with grants), **I recommend that the cost estimates for the entire decision tree be refreshed, and the decision be retraced. We cannot be sure we are minimizing cost if we do not know the costs of the other options available to us.**

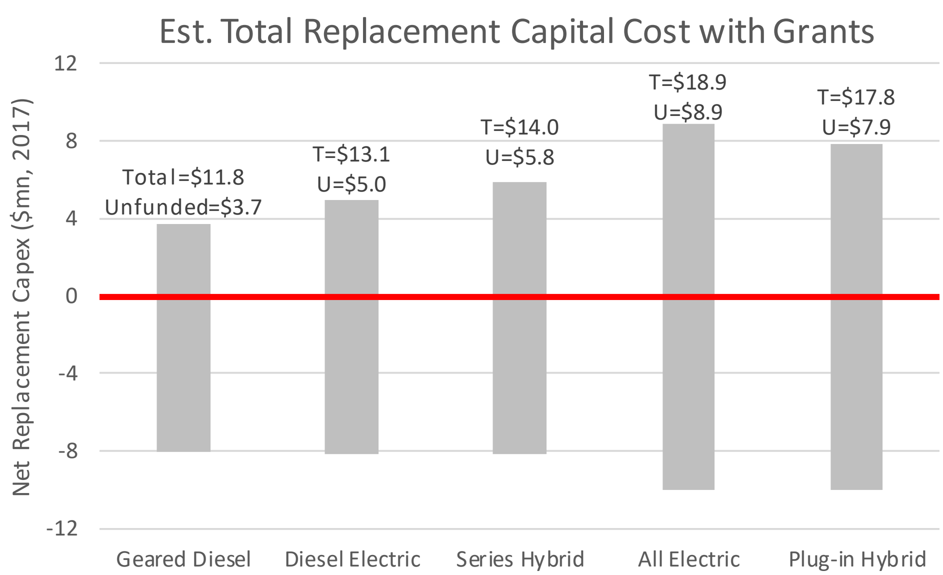
By appearing not to have a budget, we may be broadcasting a message that Skagit County is committed to buying a new electric ferry at any cost. What motivation do vendors have to rein in their costs when they know we have no appetite for alternatives? We may be emboldened by visions of grant money that we do not yet have, but that is still somebody's money, and we have a responsibility to spend it wisely. Realistically, some of the financial burden is likely to fall back onto Skagitonians, especially ferry riders.

Question 2: Can we afford to pay more upfront?

Not every organization is in a position to front-load its capital expenditures. If Skagit County bought a new ferry today, it would have to rely entirely on grants and loans.[88] This situation makes initial cost a significant hurdle for us: if the county cannot raise enough money to build a new ferry, then it cannot pursue the path that it believes offers the lowest "overall cost of ownership."[69]

Exhibit 16 compares my estimated total capital costs/expenditures (capex) for the 28-car ferry options. The total height of each bar represents <u>the total initial cost of each option, including terminal improvements and shoreside charging infrastructure as applicable</u>. The part of the bar below the thick red $0 line represents all applicable grants that we have secured.[89] The part of the bar above the thick red $0 line represents the remaining cost to Skagit County. I have assumed that the CRAB grant could apply to any ferry option because the grant announcement contains no stipulations about propulsion technology (recall my rationale on page 6 of this document).[90]

Exhibit 16. Estimated total capital costs for the 28-car ferry project, <u>including grants</u>



Originally we expected to gain leverage with specialized grants for our unique propulsion system, but after years of disappointments, the electric ferry project is only half-funded today, $8.9mn short of the estimated $18.9mn cost released in 2017.[91] Even though the diesel ferry is theoretically eligible for only the CRAB grant, its cost is so much lower that it is presently only $3.7mn away from being fully funded. **<u>If the CRAB would be willing to fund a diesel ferry, then we could immediately cut our outstanding fundraising burden by more than half by choosing the geared diesel ferry over the all-electric ferry.</u>**

Exhibit 16 may understate how much more we are paying upfront for the electric ferry, because some capital costs may have gone unreported, including but not limited to:

- The ongoing pursuit of grants, which is costly and involves many subcontractors.
- Keeping *Guemes* nearby and serviceable after it has been replaced, which the county has indicated that it intends to do.[92] The length of ferry overlap would presumably be much shorter for established propulsion technology than it would be for cutting-edge propulsion technology. The existing ferry's upkeep costs are likely to change very little in reserve, despite the reduced operating hours. On top of those costs, there would be additional costs to moor it and to monitor it. The replacement project includes widening the end of the ramp; unless this widening occurs in a later phase, *Guemes* would have to be modified in

order to continue serving the dock after the end of the ramp has been widened, adding to the yet-unreported costs.[93]

- Debt service on bonds, as applicable. The more we borrow, the more we pay in interest. An updated Replacement Plan could account for the cost of bond debt in its discount rate.
- A reserve fund for capital-cost overruns. Overrun potential is larger in likelihood and magnitude for projects with higher equipment costs and lower "complexity" ratings.

Question 3: Does it save more money than it costs?

Skagit County initiated the ferry acquisition process thinking that it knew the answer to this question. In 2015 and 2016, the commissioners heard sales presentations stating that Skagit County would break even on electrification (relative to geared diesel) within five to eight years, excluding grants.[70] But once Glosten completed its impartial study for our particular operation, we learned that we would actually lose $6.7mn (relative to geared diesel) over the 40-year life of the 32-car ferry, excluding grants (recall Exhibit 1, which presents lifecycle costs for the 32-car ferry on the horizontal axis).

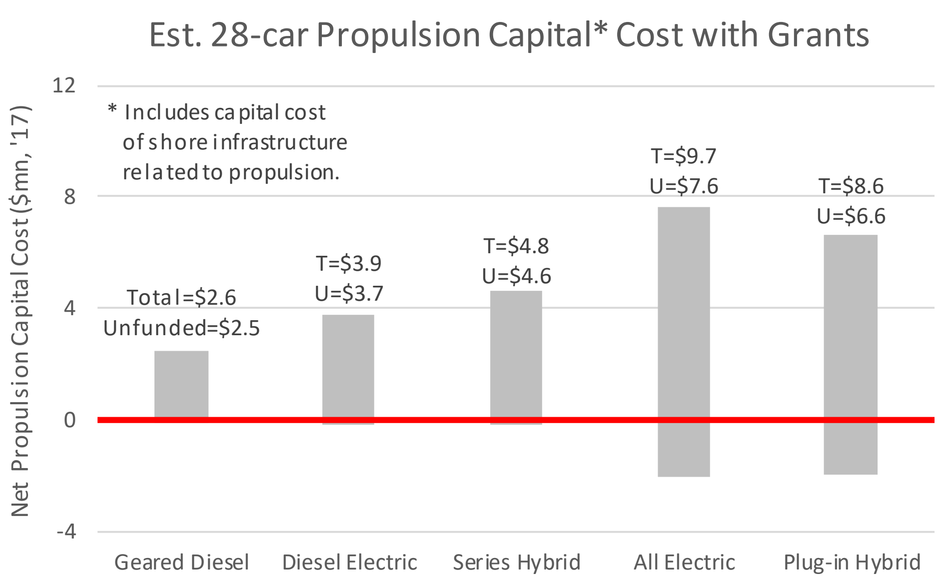
Our situation has changed since then. The county intends to build a smaller 28-car ferry, and it has received three grants, with various strings attached, to help cover capital costs.[71] To see what these developments have done to our bottom line, I will examine, and then combine, the two components of the propulsion system's lifecycle cost (see Appendix A). Lifecycle cost measures the total lifetime cost of ownership in present-day dollars. The two components of lifecycle cost are:

- **Capital costs** paid to acquire the asset and to service associated debt.[94]
- **Operating costs** paid to maintain and to operate the asset throughout its life.

Propulsion Capital Cost

Exhibit 17 presents the estimated total capital costs for just the propulsion system (e.g. engines, batteries, and labor), including all required shoreside infrastructure, per my calculations in Appendix A. The part of the bar below the thick red $0 line represents all propulsion-specific grants that we have secured.[89] The part of the bar above the thick red $0 line represents the remaining cost to Skagit County. **The all-electric propulsion system costs four times more than the geared diesel system does.** After including the propulsion-specific grants, it still costs three times more.

Exhibit 17. Estimated capital costs for the 28-car propulsion system, including grants



Propulsion Operating Cost

Exhibit 18 presents the estimated present value of 40-year lifetime operating expenditures (opex) for just the propulsion system (e.g. fuel, electricity, and propulsion-specific maintenance). As I understand it, the county's financial strategy is to find grants to pay for the entire ferry replacement program's capital costs, so that we only have to cover operating costs and repairs. If this strategy works—and if repair costs remain low—then **the electric ferry is indeed alluring, because its estimated operating cost is 39% lower than that of the geared diesel ferry.**

Exhibit 18. Estimated total lifetime operating costs for the 28-car propulsion system

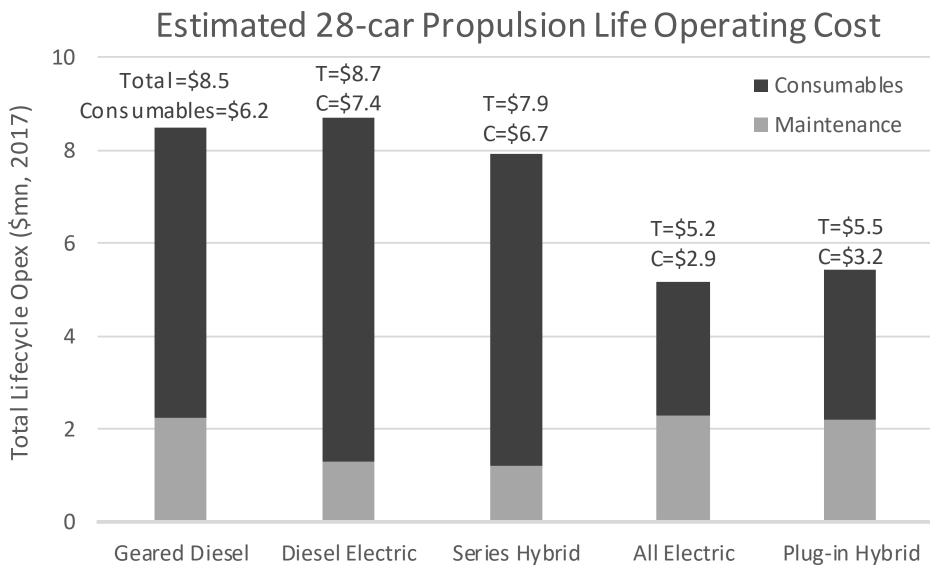


Exhibit 18 may understate our operating expenses for the electric ferry, because some associated costs may have gone unreported, including but not limited to:

- Insurance premiums. We may find that electric passenger vessels carry different insurance premiums than diesel passenger vessels do.
- Towing the ferry to shipyards for routine maintenance. With such limited range, the electric ferry may be unable to travel on its own power to any shipyard other than Dakota Creek.[95]
- A reserve fund for operating cost overruns. Overrun potential is larger in likelihood and magnitude for projects with higher equipment costs and lower "reliability" ratings.

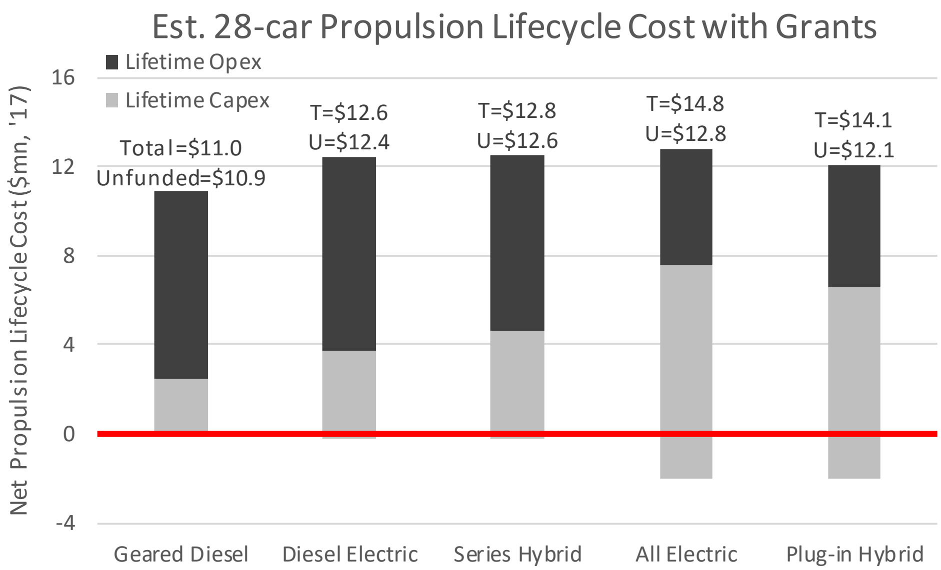
Propulsion Lifecycle Cost

I added together the capital and operating costs, net of grants, to come up with the total 40-year lifecycle propulsion cost to Skagit County. These figures represent the total cost of acquiring and using the ferry's propulsion system over a 40-year lifespan. Since the base-model ferry is presumed to be the same, and the variations are limited to the propulsion system, the propulsion lifecycle cost captures the estimated differences in the lifetime cost of vessel ownership.

These are the costs represented in Exhibit 19. The gray bar represents propulsion capital expenditures (capex), with the unfunded portion floating above the thick red $0 line (i.e. the part covered by grants is below $0). The black bar represents the total present value of 40-year propulsion operating expenditures (opex). Thus, the total height of the bars above the $0 line represents the net propulsion lifecycle cost to Skagit County, including all propulsion-specific grants that we have secured.[89]

Even with today's propulsion-specific grants in hand, we are still $1.9mn away from breaking even on the electric ferry, relative to the geared diesel ferry, over the course of its lifetime. Worse yet, we need to spend an extra $5.1mn of our own money right now (Exhibit 17) in order to save $3.3mn over the next 40 years (Exhibit 18). **<u>It makes no sense to borrow $5mn now—with interest—in the hope of getting only $3mn back over a period of decades.</u>**

Exhibit 19. Estimated total lifecycle costs for the 28-car propulsion system, <u>including grants</u>



It is also worth pausing to reflect that without grants, the lifecycle cost of the all-electric propulsion system is $3.8mn (35%) higher than the lifecycle cost of the geared diesel propulsion system. **<u>We are asking other public agencies to subsidize a project that appears to make very poor financial sense.</u>**

Sometimes a decision that makes poor financial sense can be justified by the nonfinancial benefits that it offers. Skagit County and Glosten created the propulsion scoring system (the vertical axis in Exhibit 12) to account for desirable traits that are not captured in the price, such as reliability and environmental friendliness. The electric and hybrid ferries had lower total Skagit-Glosten scores than the diesel ferries did, which is to say that **<u>Skagit County has provided no justification for choosing an electric ferry on nonfinancial grounds either.</u>**

Question 4: How reliable are the cost estimates?

In my answers to the past three questions, I have made comparisons with estimated costs, assuming that those estimates represent what the actual costs will be in the coming decades. Sometimes we need to step back and remember that these cost estimates are just our best guesses—and that not all guesses are equal. Think back to Glosten's "design and build complexity" scores for the all-electric and plug-in hybrid ferries: they were zero, the lowest possible score, because there is great potential for unforeseen complications and cost overruns during construction and beyond. Glosten's score for the geared diesel ferry was one, the highest possible score, because the path is well-worn, and its construction and maintenance costs are highly predictable.

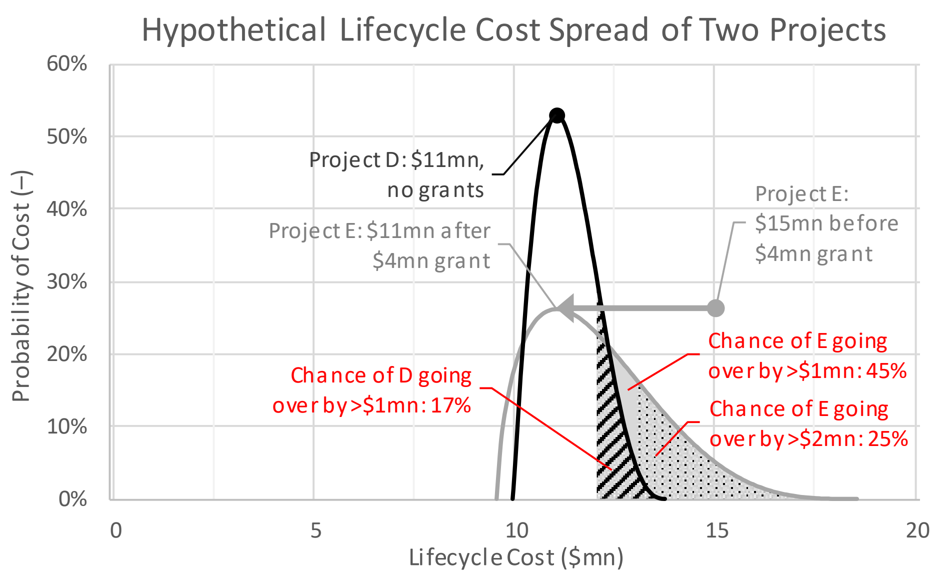
To understand why the electric vessels' scores are so much lower, consider this statement from page 32 of the Concept Design Report:

> **An average industry standard battery bank life is six to ten years. An eight-year battery life was chosen as a baseline for the comparison in this report.**[96]

The cost estimates for our ferry are based on the batteries lasting eight years, but they are expected to last anywhere from six to ten years <u>on average</u>. That is an expected variability of ±25%, which is highly variable for the average lifespan of a major component. If those are just the averages, then what are the extremes, and how likely are they to occur? A full set of ship and shore batteries costs almost a million dollars.[97] **Where does that money come from if we need to replace the batteries in year six—or even year three—instead of year eight?**

I created Exhibit 20 to illustrate how this kind of greater uncertainty exposes us to greater financial risk. The two curves represent hypothetical probability distributions for two generic projects that have roughly the same lifecycle costs as the 28-car geared diesel and all-electric propulsion systems do (Projects D and E respectively). The horizontal axis represents the range of possible outcomes in lifecycle cost. The curves represent the probability that any of those possible outcomes would become reality, with probability measured on the vertical axis. **This plot is hypothetical for the purpose of illustrating a concept.** The details of how I created Exhibit 20 are provided in Appendix C.

Exhibit 20. Hypothetical lifecycle cost spread for Project D and Project E



The peaks of the curves represent the most likely lifecycle costs. Project D is expected to cost $11mn over its lifetime, with no grant eligibility. Project E is expected to cost $15mn over its lifetime, but it is eligible for a $4mn grant that brings its expected cost down to $11mn too. The best choice is obviously Project E, because we get $4mn for free—right?

Not so fast. Look at the shapes of the two probability distribution curves. Project D has a much narrower spread, meaning that the range of possible cost outcomes is also much narrower. Project E's curve is much more spread out, especially to the right, where costs are high. This means that **Project E has a much greater probability of cost overruns, and those cost overruns could be much greater than the worst-case cost overrun with Project D.** There is no grant available for those cost overruns: they fall squarely on Skagit County's shoulders.

The shapes of these curves are determined by two characteristics:

1. The spread of outcomes. Project D is mature technology: its range of outcomes has a narrower spread, because the kinks have been worked out. Project E is immature technology: its range of outcomes has a wider spread, because there are many potential surprises.
2. The cost basis. Cost uncertainty applies to the actual costs of the projects before grants. Project D costs $11mn, whereas Project E costs $15mn.

Taken together, the greater spread of outcomes multiplied by the higher cost basis makes the cost of Project E much less predictable. The range of possible costs for Project E spreads out farther—especially to the right, where costs are extremely high.

The shaded and textured areas in Exhibit 20 represent the total probabilities of serious cost overruns in this hypothetical scenario. The hatched area represents the probability that the lifecycle cost of Project D turns out to be at least $1mn more than expected: 17%. The shaded area represents the probability that the lifecycle cost of Project E turns out to be at least $1mn more than expected: 45%. The dotted area represents the probability of Project E going over by at least $2mn: 25%. Project E has a much higher chance of going over budget by an amount of money that would pose a serious hardship to a small, cash-strapped organization like Skagit County. Exhibit 20 shows how easy it is to take on excessive financial risk when we choose a cutting-edge project that has a higher cost before grants are included. **We cannot choose where we end up on those curves, but we can choose which curve we end up on.**

We will not know our ferry's actual lifecycle cost until the end of its life. This is why existing vessels' lifetime performance data are so important: we can use other operators' past experiences to anticipate our future experiences—not just the averages, but also the extremes, and the likelihood of everything in between. We have a long and rich history of millions of diesel vessels' complete lives. Meanwhile, the world's oldest battery-assisted car ferry is just seven years old, and only 23 others are currently operating on this planet.[98] This lack of data means we cannot predict the lifecycle costs of an electric ferry with nearly as much confidence as we can predict the lifecycle costs of a diesel ferry. This is a serious problem for a small county that has had trouble navigating the minor financial shocks dealt by the simple ferry in service today.[22] Even if grants eventually bring the estimated lifecycle cost of the all-electric ferry down to the range of the geared diesel ferry, the all-electric ferry's actual lifecycle cost remains a major wildcard. **Skagit County cannot afford for the replacement ferry to be anything less than average—and that is an unrealistic expectation for new technology.**

Grants rarely amount to free money, especially when they are contingent on using cutting-edge technology. **By accepting those grants, we are selling our risk at a price somebody else has set.** Consider this passage written by the Guemes Island Ferry Committee:

> **We believe that an electric or electric-hybrid ferry is the best technology for future efficient operation and to protect our environment. This technology and these environmental concerns coincide with Washington State's plans to convert their fleet of ferries to more environmentally sustainable energy sources. They view our modest ferry proposal as [a] test case for their planning.**[99]

Several months later, the Washington State Legislature contributed $1.5mn to help fund the electric ferry's shoreside charging station (total estimated cost: $3.8mn).[100] If state officials see this grant for electrification as an investment in a "test case for their planning," then there seems to be an element of risk that Washington State is eager to subcontract to Skagit County for a firm price of $1.5mn. **If anything unfortunate happens to our electric ferry, our benefactors get the case study and we get the bill.**

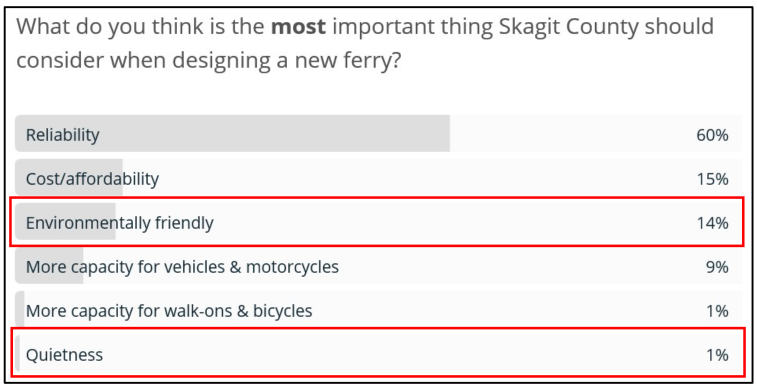
Principle 3: We are still environmentalists.

Key Ideas:

- There are many contributors to the total environmental impact of a vehicle.
- An electric vehicle's CO_2 emissions depends partially on the source of its electricity.
- An electric Guemes ferry reduces CO_2 emissions by 57% relative to geared the diesel ferry.
- Established projects on land could be much more effective at reducing CO_2.
- Airborne noise could be reduced with any propulsion option, including geared diesel.
- Electrification does little to relieve underwater noise in Guemes Channel.

Returning once more to the design priority poll (Exhibit 21), we see that 14% of respondents said that being "environmentally friendly" was the most important design consideration. To this group I have added the 1% of respondents who prioritized "quietness," which I believe is also an environmental consideration.[15] With this nudge, **one could argue that the public's concern for the environment is as high as its concern is for cost.**

Exhibit 21. Design priority poll results, with emphasis on environmentalism and quietness



When Skagit County created its scoring system for propulsion options, it devoted 25% of the total score to environmental considerations through two categories:[101]

- 15% "vessel air emissions," which Glosten defined as "the local engine exhaust emissions, measured in particulates."
- 10% "airborne noise," which Glosten defined as "airborne noise created on the vessel from engine operation."

This weighting suggests that **Skagit County believes environmental stewardship is an important consideration, but not the top priority,** for reasons I have already explained. Even though environmentalism has proven not to be our top priority in ferry replacement, we are still environmentalists. We still want to make decisions that are good for the planet. This chapter shows how we can still be good to our planet even if we do not choose an electric ferry—and how **we might actually help our planet more by not choosing an electric ferry.**

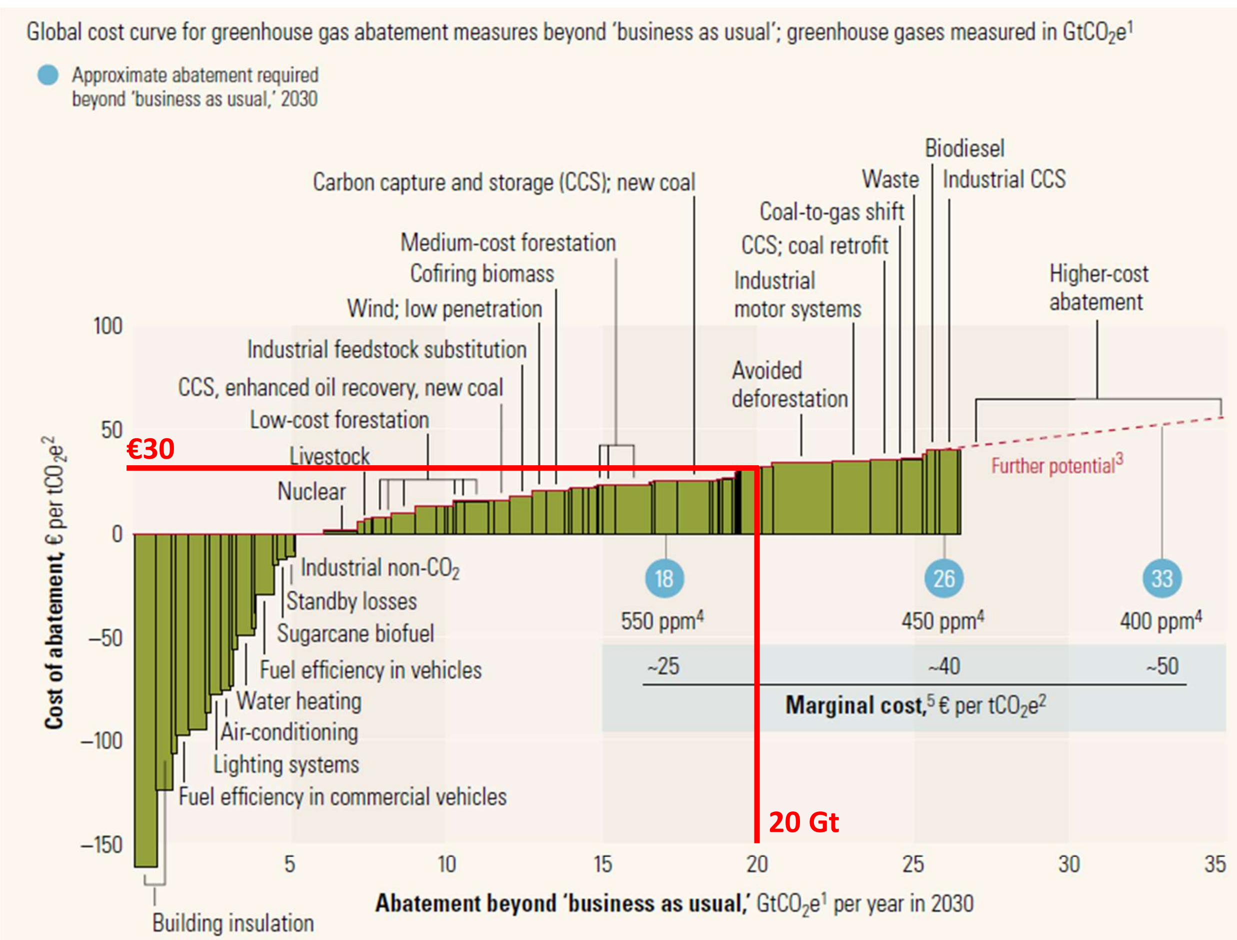
Environmental impact is a multifaceted concept, and it changes over time with the advancement of science and the evolution of societal values. Humanity seems to be focused on greenhouse gases today, so much of my discussion focuses on that topic. I also discuss noise because it appears on the poll. My omission of other aspects is not for a lack of concern.

The Economics of Greenhouse Gases

The Intergovernmental Panel on Climate Change (IPCC) estimates that **humans must cut their carbon dioxide (CO_2) output over the next decade by 25% to 45% to avoid causing more than 1.5°C to 2.0°C of global temperature rise.**[102] A reduction this steep could only be achieved through sweeping changes in government policies and capital investment strategies. Yet even the governments and Gates Foundations of the world have limited funds with which to combat climate change. **In order to have the most impact on a finite budget, policymakers look for the programs that yield the biggest greenhouse gas reduction per dollar spent, because those programs offer the best chance of slowing global warming with limited funds.**

McKinsey, an international consulting firm, created a "marginal abatement cost curve" to propose a method for stretching our decarbonization dollars the farthest (Exhibit 22).[103] Each bar represents an intervention that reduces humanity's annual CO_2 output.[104] The width of the bar represents the amount of CO_2 reduced annually by each intervention (horizontal axis). The height of the bar represents the cost per ton of CO_2 reduced (vertical axis). Interventions below the €0 line ultimately save the investor money—e.g. installing better building insulation. Interventions above the €0 line ultimately cost the investor money—e.g. industrial carbon capture and storage (CCS).

Exhibit 22. McKinsey marginal CO_2 abatement cost curve



[1] $GtCO_2e$ = gigaton of carbon dioxide equivalent; "business as usual" based on emissions growth driven mainly by increasing demand for energy and transport around the world and by tropical deforestation.
[2] tCO_2e = ton of carbon dioxide equivalent.
[3] Measures costing more than €40 a ton were not the focus of this study.
[4] Atmospheric concentration of all greenhouse gases recalculated into CO_2 equivalents; ppm = parts per million.
[5] Marginal cost of avoiding emissions of 1 ton of CO_2 equivalents in each abatement demand scenario.

McKinsey proposes the implementation of the lowest-cost abatement measures first, up to the point where the desired CO_2 reduction is achieved. You can see this approach graphically by stacking up the bars from left to right and then reading the corresponding CO_2 reduction on the horizontal axis.

Given the world's current CO_2 output of roughly 40 billion metric tons (gigatons, or Gt) per year,[105] the IPCC estimates that we need to reduce our CO_2 output by roughly 20 Gt per year by 2030 to limit warming to 1.5°C.[106] At the 20 Gt mark on Exhibit 22, the marginal cost appears to be roughly €30 (I have added annotations for emphasis). In McKinsey's idealized world, we could achieve the IPCC goal by spending no more than €30 per metric ton of CO_2 in 2030, or about $34 in 2020 US dollars.[107]

Governments around the world have worked to answer the same question—how much should we spend to prevent a ton of CO_2 from being released?—but they have approached it from a different angle. Given their mission to protect the public, governments have focused instead on calculating the cost that society incurs when a ton of CO_2 is released. Government carbon prices are calculated as "the costs of emissions that the public pays for, such as damage to crops, health care costs…, and loss of property."[108] These costs are then used to reduce CO_2 emissions through taxation, subsidies, and regulations. **"Carbon pricing encourages emissions reductions at least cost,"[109] because for many CO_2 emitters, it would be cheaper to clean up their act than to pay the tax.** In Washington State, a metric ton of CO_2 is priced at $77 in 2020.[110] At the federal level, the price is $53.[111]

Airborne CO_2 Emissions

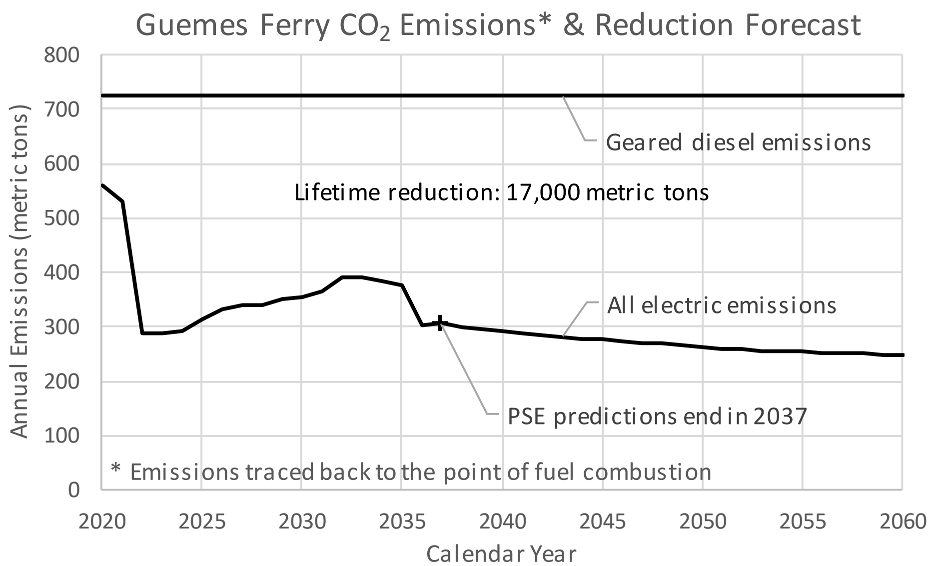
According to Skagit County's ferry replacement website, "an all-electric vessel would potentially… reduce harmful CO_2 (carbon dioxide) air emissions by 619,359 kg" (619 metric tons) per year.[112] I cannot find the county's documentation for this number; it appears to describe the amount of CO_2 released from the existing ferry's exhaust stacks.[113] A reduction in local air pollution would be a good outcome—most importantly for the crew, and also for riders and neighbors—but gases do not respect county lines.[114] **An accurate assessment of greenhouse gas emissions—or of any other environmental consequence—must consider every upstream contributor to our ferry's construction, operation, maintenance, and disposal.**

To illustrate my point, I took the next logical step toward a thorough accounting of our ferry's environmental impact: calculating CO_2 emissions wherever the fossil fuels are burned, be it in our engines or in Puget Sound Energy's (PSE's) powerplants (see Appendix D). This approach is still imperfect and distorted in many ways. It omits the impact of extracting, refining, and transporting these fuels. It omits the impact of making and discarding equipment like engines and batteries. My choice to take only one step toward understanding the complex environmental impact of our ferry reflects only a lack of time, not a lack of curiosity.

PSE foresees some major mandatory changes in the coming years, most notably a transition from coal to natural gas.[115] I used PSE's emissions forecasts to create Exhibit 23, which shows annual CO_2 emissions forecasts for the all-electric and geared diesel ferries over their nominal 40-year lives, from 2020 to 2060.[116] An explanation of these calculations is provided in Appendix D.

The all-electric ferry reduces CO_2 emissions at the point of combustion by an average of 420 metric tons per year—but that means it is still emitting 310 metric tons of CO_2 at the powerplants. Better? Certainly. Zero emissions? Certainly not. But that is not the most important point.

Exhibit 23. Forecasted 28-car Guemes ferry CO_2 emissions



For boats and airplanes, using batteries as "fuel" creates expensive problems with weight, range, reliability, and fire safety. These kinds of problems are either nonexistent or easier to solve at noncritical terrestrial facilities that are closed to the public. This is one reason why all of the interventions called out in Exhibit 22 occur on land, and why most of them involve changes to industrial, agricultural, or manufacturing processes.

Glosten observes that the range requirements for heavy weather and emergencies are "difficult to meet" in a ferry that relies on batteries, whereas they are "easily achieved on a diesel-powered ferry."[117] **<u>Skagit County ends up having to spend a lot of extra money to make up only partially for the electric ferry's shortcomings in abnormal situations, even though that extra investment is expected to go unused on most days.</u>**

I established in Exhibit 19 that some combination of taxpayer-funded organizations is paying a premium of \$3.8mn over the ferry's lifetime (\$3.9mn in 2020 dollars)—and, per Exhibit 17, \$7.1mn upfront (\$7.2mn in 2020 dollars)—so that we can have an all-electric ferry instead of a geared diesel ferry.[91] We know that there is public and governmental sentiment in favor of spending additional money to reduce CO_2 emissions. From that perspective, just how good of an investment is an electric ferry?

We established in Exhibit 23 that choosing electricity over diesel is likely to reduce our CO_2 output by 17,000 metric tons over 40 years, if we follow the emissions stream back to the point of hydrocarbon combustion. That comes to a premium of \$230 per metric ton of CO_2 by simple division, or \$170 per metric ton of CO_2 using Washington State's discounting schedule for future greenhouse gas emissions.[118] **<u>Relative to other CO_2 pricing and abatement strategies, an electric Guemes ferry is an inefficient use of public funds,</u>** as Exhibit 24 demonstrates.[119] The horizontal axis contains a range of approaches to CO_2 pricing, from social costs on the left to some general and energy-related abatement actions on the right. The vertical axis contains the price per metric ton of CO_2 in today's dollars.

Based on this analysis at the point of combustion, I believe we may be paying two to three times the social cost per ton of CO_2—and several times the cost per ton of other CO_2 abatement interventions—which suggests that **<u>buying an electric ferry with money earmarked for reducing greenhouse gases may not serve the best interest of the public.</u>**

Exhibit 24. Comparison of CO_2 social and abatement costs

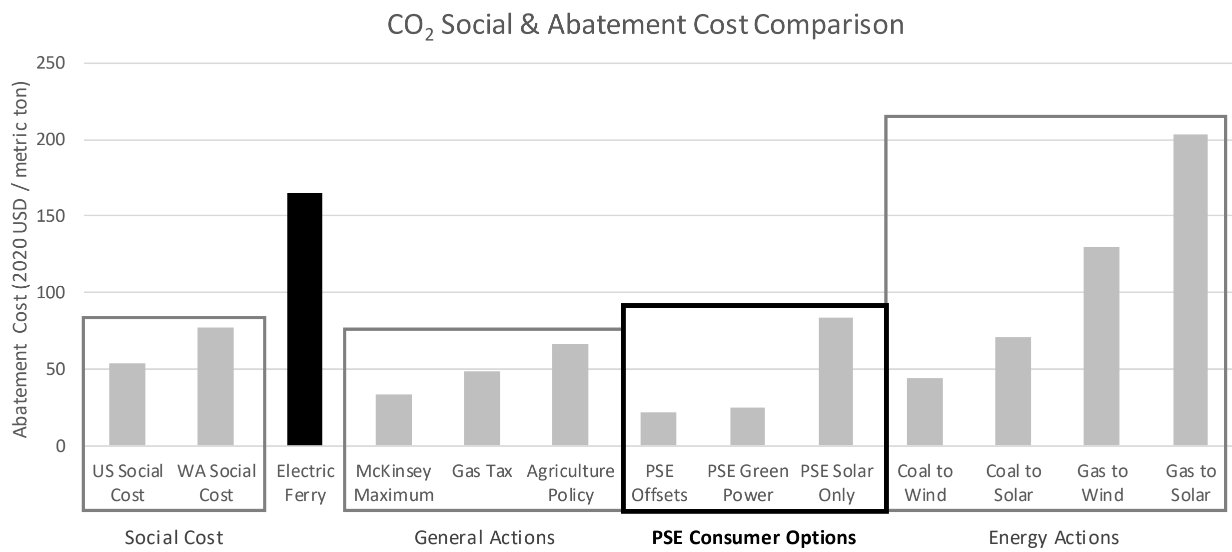


Exhibit 24 shows examples of some other actions that would reduce CO_2 emissions for similar or lower cost, and in many cases below the social cost—including low-cost abatement options available to PSE consumers today. For the same amount of extra money that we are spending to electrify, we could do much more to reduce atmospheric CO_2 by choosing more established abatement technologies—and those projects would not pose nearly as much operational or financial risk to the people of Guemes Island or the government of Skagit County.

The electric ferry does have one advantage over these other projects: a political path to completion. It would be difficult to change agricultural policy, and we have already seen carbon taxes fail twice at the state polls. With that in mind, it certainly makes sense to mount a serious effort to curb greenhouse gases at the county level, where the idea enjoys sufficient popular support. My concern is that **we are conflating two issues into one—and we feel a lot of external pressure to do so, even if it is not in our own best interest.**

First, there is the issue of replacing the ferry. Through a painstaking and objective evaluation process, Skagit County's impartial expert concluded that a diesel ferry is superior to an electric ferry for serving Guemes Island (recall Exhibit 1). This conclusion is politically inconvenient: it contradicts the county's original narrative, and it puts the county at odds with a narrative that has become popular worldwide. Few people want to be perceived as anti-progress or anti-environment. Yet the goal of the Guemes ferry replacement program is, quite simply, to acquire a new ferry that is best suited to Skagit County's needs. **An unbiased expert concluded that the best option is a diesel ferry,** even when environmental impact is accounted for.

Second, there is the issue of reducing greenhouse gas emissions. Skagit County created the Climate Change and Sustainability Initiative in 2008 to address this issue head-on.[120] This initiative seems to support the kinds of low-cost, high-impact projects championed by McKinsey (Exhibit 22). According to the county's website, most of the activity related to this initiative had ended by 2013. If anthropogenic climate change remains one of Skagit County's top priorities, then **the Climate Change and Sustainability Initiative might be overdue for a revival.** The $5.1mn capital premium that Skagit County seems ready to pay "out of pocket" for an electric ferry (Exhibit 17) could probably go farther to reduce CO_2 emissions—and to save money, and to protect Skagitonians—through the Climate Change and Sustainability Initiative, by investing in projects that reduce energy consumption, waste, and pollution.

Looking beyond internal initiatives, Skagit County could team up with PSE on a regional project that adds renewable generation capacity or peaking battery storage, both of which are likely to do more for the environment than an electric ferry would.[121] The City of Anacortes, Whatcom County, and many other local governments are already supporting PSE's renewable projects as Green Direct partners. **Skagit County is not part of PSE's Green Direct program.**[122]

If Skagit County preferred a more flexible budget with the greatest impact per dollar spent, then it could buy third-party-verified carbon offsets, which is a way of investing globally in the many low-cost, high-impact CO_2 abatement opportunities identified in Exhibit 22 and Exhibit 24. According to one purveyor of verified carbon offsets, **the premium paid for the electric ferry could eliminate 30 to 50 times more CO_2 if it were invested globally in low-cost, high-impact carbon offset projects instead:**

The average offset prices are between roughly \$3-\$6 per ton.[123]

It is also important to recognize that **there are many interventions to reduce ferry-related CO_2 emissions that have nothing to do with electrification.** Engineers had to find a way to cut Norled *Ampere*'s energy consumption in half to make electrification possible on the Lavik-Oppedal route. For Skagit County, any reduction in energy consumption leads to a proportional reduction in CO_2 emissions, regardless of whether that energy comes from diesel fuel or PSE's electricity. Norled's energy-saving measures include:

- **Reducing vessel weight.** Weight and energy consumption are closely related on ships. Norled built the entire ferry's structure out of aluminum to reduce weight. Norled also designed the ferry so that no ballast would be needed, further reducing weight. As a result, *Ampere* weighs only about half as much as the other ferries on the route do.[32,124]
- **Reducing hull drag.** Norled designed a sleek asymmetric catamaran hull to reduce energy consumption. According to Norled, the combination of reduced weight and drag led to a 40% decrease in energy consumption.[32] It is possible that the hull was computer-optimized to minimize hull drag at cruising speed. Washington State Ferries used computer optimization to achieve a significant reduction in hull drag on its new Olympic-class double-ended ferry.[125] Optimization must be wielded carefully, because it usually involves compromises in other aspects of design or performance.[126]
- **Increasing propeller efficiency and reducing propeller drag.** *Ampere* was designed to include large, slow-turning propellers to maximize propulsive efficiency. *Ampere* uses only one propeller at a time; the blades on the unused propeller flip out of the way to minimize drag. According to Norled, these measures reduce energy consumption by 7%.[32]
- **Using an automatic docking system at both terminals,** so that *Ampere* does not need to hold itself against the dock using propeller thrust (i.e. pushing), which is inefficient. The CDR states that Skagit County could reduce total energy consumption by 12% if it installed an automatic docking system at the Anacortes terminal.[127]

These energy-saving measures generally require additional capital costs, but the money saved in operation through reduced fuel or electricity consumption could result in a net lifecycle cost savings for Skagit County. If not, then the net lifecycle cost of each option (i.e. the remaining cost after savings) could be converted to a marginal CO_2 abatement cost and compared with the CO_2 abatement costs of other options available to us—including electrification.

Some of the energy-saving measures used on *Ampere* have already been ruled out for our ferry.[128] Yet there are other energy-saving measures that are unique to our ferry. When the commissioners decided to build a 28-car ferry instead of a 32-car ferry, they reduced the ferry's energy consumption—and thus its CO_2 emissions—by roughly 24%.[129] I applaud the commissioners for choosing a more modest ferry that is inherently more environmentally friendly.

This point about modesty underscores my concern that our society's obsession with "green" (or "Maritime Blue") technology makes it easy to overlook the power of making humbler lifestyle choices.[130] Anthropogenic climate change is ultimately driven by our addictions to comfort, convenience, and leisure. **I cannot envision any realistic technology rollout scenario that would achieve the IPCC goal by 2030. To get there, those of us with high carbon footprints must also change the way we live.** We could substantially reduce greenhouse gas emissions by making different choices about what we eat, what we buy, and how (and how much) we travel—to name a few of the more impactful choices.[131]

We could apply a similar "behavioral audit" to our relationship with Guemes Island. In the recent ferry operations survey, many of us supported adding more scheduled ferry runs.[132] Every additional scheduled run increases the Guemes ferry's CO_2 emissions by 4%.[133] Every time an eco-tourist drives round-trip from Seattle to ride the electric ferry, they cancel out three crossings' worth of CO_2 savings relative to the geared diesel ferry.[134] Every new summer cabin on the island cancels out four days' worth of CO_2 savings each year, excluding construction emissions.[135] If we could convince 10% of drive-ons not to idle for 10 minutes in line, we would cut almost as much CO_2 emissions each year as a week's worth of electric ferry operation does.[136]

Electrification is seductive because it turns the mirror away from us: it separates the action from the consequence, the effortless trip across Guemes Channel from the energy it consumes and the pollution it creates. This psychological effect is especially alluring for us, because *Guemes*'s engines are impossible to ignore. When there is no "clanking, wheezing, belching internal combustion engine" affronting us, then our harm to the planet becomes plausibly deniable.[137] Yet **replacing the most obvious direct CO_2 emitters with the most newsworthy indirect CO_2 emitters is an unscientific way to combat climate change.** If we are to have any hope of reaching the IPCC's goal by 2030, then we must be scientific about our use of technology and capital, we must sacrifice the most harmful aspects of our decadent lifestyles, and we must be swift in our adoption of these reformations.

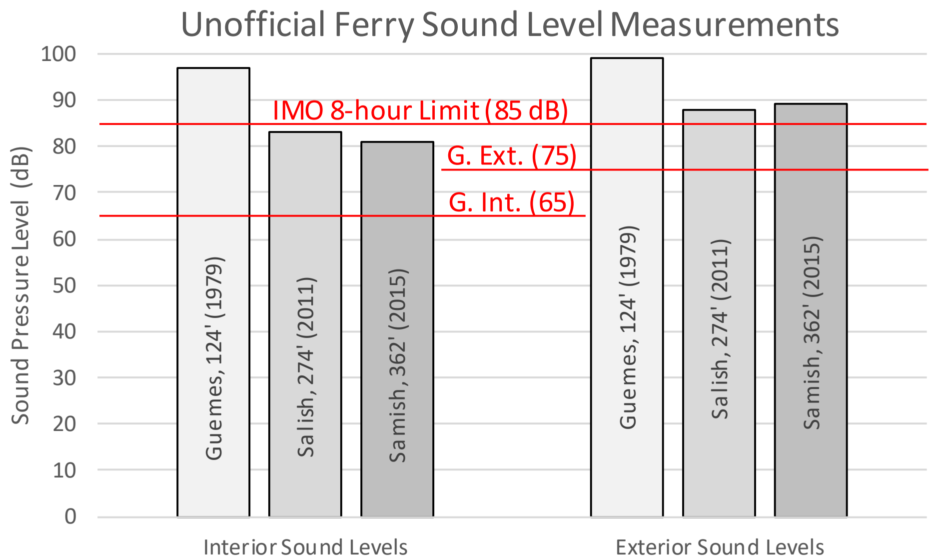
Airborne Noise

Airborne noise is a problem for the existing ferry: it harms the crew, contributes to local noise pollution, and hampers passengers' ability to connect through conversation. I recently took some unofficial sound level measurements at cruising speed on *Guemes* and on two modern diesel ferries. Results are shown in Exhibit 25, along with the International Maritime Organization's (IMO's) recommended exposure limit of 85 decibels (dB) for up to eight hours without hearing protection.[138] I also included Glosten's proposed exterior (75 dB) and interior (65 dB) noise limits.[139] **The modern ferries exhibit lower noise levels because of four main reasons: higher standards, better materials, better engineering, and better engine locations.**

Guemes's engines are located on the car deck behind ineffective enclosures. The design for the new Guemes ferry indicates that the propulsion engines would be installed belowdecks, like they are on the other ferries in Exhibit 25.[140] **A new diesel Guemes ferry could probably have noise levels similar to those of other modern diesel ferries,** although sound attenuation is generally more challenging on smaller vessels.[141]

An electric ferry would probably have lower airborne noise levels than these diesel ferries do. However, the exact noise level is unclear, as I have not been able to find publicly available sound measurements from electric vessels. Machinery noise is ever-present on ships: compressors, pumps, and fans broadcast noise and vibration through the air and through the structure. All of our new ferry's propulsion options have gears and propellers that transmit noise and vibration into the hull. Aerodynamic and hydrodynamic noise levels increase with vessel speed, regardless of the type of propulsion system.

Exhibit 25. Unofficial airborne noise levels measured aboard three diesel ferries



I think one of the most important goals with any Guemes ferry refit or replacement is to reduce the crew's noise exposure as much as possible, with a focus on the exterior during loading/unloading and on the interior during the crossing. The 85-dB IMO limit seems like a minimum standard. If we could achieve lower noise levels at a reasonable cost, so much the better.

Underwater Noise

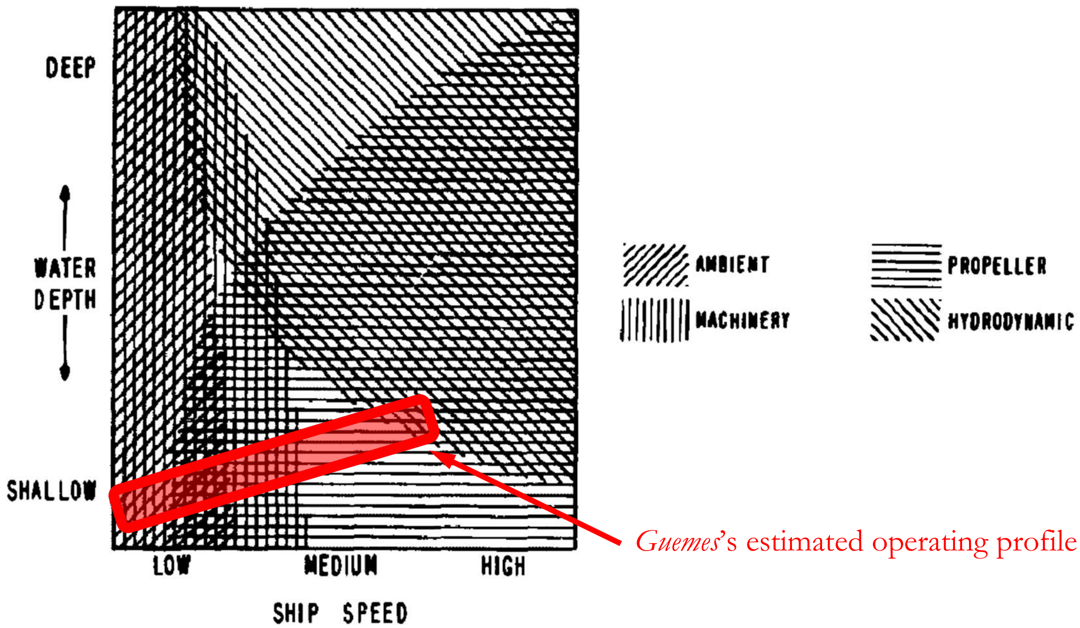
The press has embraced the idea that eliminating engine noise is "orca-friendly."[142] Yet **we should be careful about imposing our human biases on animals,** because they hear different frequencies, and boats sound different underwater than they do in the air. Exhibit 26, reproduced from a declassified Navy report, helps us understand that boats produce underwater noise from many sources besides engines—including pumps, gears, propellers, and even the hull as it moves through the water.[143] Even if we were to eliminate the diesel engines, the rest of these noise emitters would still be present. Moreover, the "ambient" underwater noise in Exhibit 26 is caused by many natural phenomena, including current and waves.[144] Exhibit 26 also shows how water depth (vertical axis) and vessel speed (horizontal axis) affect the prominence of those different noise sources. Although it is difficult to plot data on a graph with qualitative axes, I used my knowledge and intuition to draw a box where I believe *Guemes* operates.

Among all these sources of underwater ship noise, the propeller is the most significant contributor, according to a consortium of respected scientists and engineers:

> **Propeller-induced cavitation (the formation and rapid collapse of bubbles) is the main source of underwater sound produced by ships.**[145]

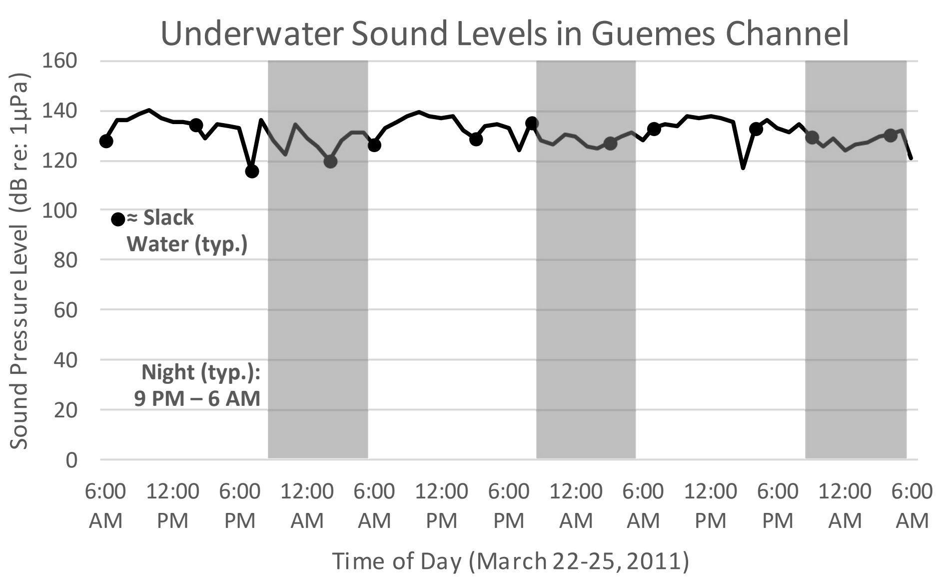
Since all variants of the Guemes ferry appear to use the same size and type of propeller,[146] **electrification offers no relief from the most significant source of underwater noise.** Regardless of which propulsion system we choose, we could optimize our propeller design for minimal cavitation—but that requires sacrificing efficiency,[147] which increases CO_2 emissions and operating costs. The design process is always a series of compromises.

Exhibit 26. Underwater noise sources from ships, with *Guemes*'s operating profile overlaid



Within Guemes Channel, there is almost constant commercial and recreational traffic. **<u>These other vessels are unlikely to electrify en masse within our new ferry's lifetime,</u>** because today's known battery technologies cannot provide the range, flexibility, and economy that most vessel owners require. Fast currents create an underwater cacophony as they rip through our narrow, hourglass-shaped channel studded with disruptive piers and marinas. Exhibit 27 presents underwater sound level measurements in western Guemes Channel taken in March of 2011.[148] There is a lot of constant background noise in Guemes Channel: roughly 120 dB worth, whereas the background noise is closer to 80 dB beyond the continental shelf.[149,150] Noise levels are generally lower during nighttime and higher during daytime, suggesting the influence of human activity. Noise levels are also generally lower during slack water and higher between slacks, suggesting the influence of current. I found a strong correlation between current speed and noise level.[151]

Exhibit 27. Underwater noise measurements at the western entrance to Guemes Channel



Among all of these natural and anthropogenic noise sources, our ferry is most likely a minor contributor to Guemes Channel's total underwater noise profile. Underwater noise pollution is strongest in the frequency range where ships' propellers operate,[152] and we have established that electrification does nothing to solve the problem of propeller noise. Taking out the diesel engines might make the water around our ferry a tiny bit quieter, but **the overall reduction in Guemes Channel's underwater noise profile seems likely to be so small that it is difficult to justify all of the extra risk and cost.**

As with CO_2 abatement, there are probably simpler interventions that would be more effective at helping the orcas. Governor Inslee's office recently released a report on exactly this subject. The 49 recommendations in that report cover a wide range of ideas on land and sea, including quieter propellers and electric propulsion.[153] A recent Canadian report regarding the impact of noise pollution on cetaceans offered 32 recommendations for reducing vessel-borne underwater noise. Of those 32 recommendations, only two involved electric propulsion.[154]

Why Not a Hybrid?

When I explain the disadvantages of electric vessels to people, they often ask if a hybrid vessel would be a good compromise between battery technology and diesel technology. I think it is necessary to include a response to that inevitable question in this document.

The term "hybrid" can mean a lot of things in the world of electric vehicles. It generally denotes a propulsion system that uses a combination of onboard batteries and onboard fossil fuels to store energy. Some hybrids get all of their energy from onboard fossil fuels; they only use the batteries as intermediate storage. Other hybrids—generally those called "plug-in hybrids"—get some of their energy from the electrical grid (which may come from fossil fuels) and some of their energy from onboard fossil fuels.

No device is 100% efficient. Every time energy passes through a device, a bit of that energy is lost. When you have a propulsion engine on a boat, the most efficient way to use its output is to couple the engine's shaft directly to the propeller shaft. If instead you connect the engine to a generator, and then a battery, and then a motor—and some smaller components in between—you end up wasting 10% more energy.[155] The more energy you use, the more fuel you burn. The more fuel you burn, the more CO_2 you put into the atmosphere.

There are some situations in which a hybrid vehicle can use less fuel. Those situations generally occur when the engine spends a lot of time running at low or unstable power levels, which make it inefficient. A great example is stop-and-go traffic: you spend a lot of time idling, accelerating, and decelerating. That is why city mileage is generally lower than highway mileage in a gasoline-powered car. Hybrid cars like the Prius get vastly superior city mileage because they only run the engine at efficient times, and they use batteries the rest of the time. The Prius charges its batteries by running its engine periodically at a stable, high load, and by collecting energy from braking.

It is easy to see if the Guemes ferry's operating profile is enough like stop-and-go traffic to make the diesel-powered hybrid ferry (i.e. the "series hybrid") more efficient than the geared diesel ferry, because Glosten has already done the math for us. Look at Table 18 of the Concept Design Report. The series hybrid ferry, which is the nautical equivalent of a Prius, uses 113,000 gallons of diesel per year. That is 13% more than the geared diesel ferry, which uses only 100,000 gallons of diesel per year. **The diesel-powered hybrid ferry emits more CO_2 because it uses more fuel. It uses more fuel because it is less efficient than a geared diesel ferry is.** The series hybrid ferry also has a significantly higher lifecycle cost than a geared diesel ferry does. The only way I could envision that we might want a hybrid like that is if we really wanted to eliminate local engine noise and emissions during low-power situations, like loading and unloading, and we were willing to make extraordinary compromises to achieve it.

The "plug-in hybrid" ferry in the Concept Design Report is a different story. It takes its energy mostly from the grid, and it only uses its onboard diesel engines when the charging system cannot supply enough energy. This arrangement provides operational flexibility: we can reduce local CO_2 emissions by drawing from the grid most of the time, yet we have the freedom to exploit the energy density of diesel fuel when we need to extend the ferry's range on the spot. Unfortunately, as we have seen, the plug-in hybrid ferry still requires us to take on a lot of additional cost and risk, while also sacrificing performance in abnormal situations. And, as we have also seen, the benefits of operating on grid power are limited by PSE's ongoing dependence on fossil fuels. These disadvantages lead me back to my earlier point: there are many safer and more cost-effective ways to reduce greenhouse gas emissions.

Conclusion

Key Ideas:

- The low-risk, low-cost choice is the geared diesel ferry.
- The high-risk, high-cost choice is the all-electric ferry.
- A refit of *Guemes* could be part of a financially optimal ferry replacement strategy.
- Being too far ahead of your time is the same as being wrong.
- Electrification is likely to be an important part of our transition to a cleaner environment.
- Electric cars have taken a century to gain a toehold. Electric ships have not advanced as far.
- At this point, an electric Guemes ferry is too risky, too costly, and not beneficial enough.

I created a decision matrix in Exhibit 28 to summarize what we have learned from the Concept Design Report. This matrix contains four boxes to represent the intersections of low and high cost with low and high risk. In each box, I put the one option that best fits that box's description. The four boxes are as follows:

- **Low cost, low risk: Geared diesel.** It is the cheapest to build and the cheapest to own over its lifecycle. It has the second-highest composite reliability score and the second-highest overall Skagit-Glosten score.
- **High cost, low risk: Diesel electric.** Compared with geared diesel, it is somewhat more expensive to build and much more expensive to own over its lifecycle. It has the highest composite reliability score and the highest overall Skagit-Glosten score.
- **Low cost, high risk: Do nothing.** If we do not invest soon either in refurbishing the existing ferry or in building a new ferry, then Skagit County runs the risk of unpredictable breakdowns and their associated problems.[87]
- **High cost, high risk: All-electric.** It is the most expensive to build and the most expensive to own over its lifecycle. It has the lowest composite reliability score and the second-lowest overall Skagit-Glosten score.

Exhibit 28. Guemes ferry replacement decision matrix

		Cost	
		Low	High
Risk	Low	Geared Diesel	Diesel Electric
	High	Do Nothing	All Electric

Although I have focused on the acquisition of a new Guemes ferry, I have also presented evidence that the most cost-effective ferry replacement strategy could include a refit of the existing ferry. Refitting *Guemes* postpones the retirement date of the new ferry, and it allows Skagit County to reduce borrowing costs by letting its replacement funds accrue. **Without a revised economic analysis, it remains unclear whether immediate replacement is still the lowest-cost option.**

Hedge-fund billionaire Howard Marks contemplates risk frequently. Of all the insights he shares with the public, I think his best insight is this one:

Being too far ahead of your time is indistinguishable from being wrong.[156]

It is easy to see where the world is going. Humanity is poised to launch a massive decarbonization effort over the coming decades. The forefront of that effort seems to be a transition from fossil fuels to renewable electricity with battery storage. This transition will not happen overnight. It will spread outward from the places where it is easiest to achieve technically, economically, and politically.

Although the time is ripe politically, the bid to electrify our unique ferry still faces major technical and economic hurdles. These hurdles may shrink over time, as the technology continues to improve and stabilize. In the coming years, some battery-electric vessels will light the way to the future, while others will become cautionary tales. The cautionary tales will always surprise us, because nobody intends to fail.

Elaborating on his quotation, Howard Marks once said that an investor who bets big and wins has still failed, because in order to win, they had to wager more than they could afford to lose.[157] This is why I believe Skagit County cannot win with an electric ferry, even if it gets lucky and dodges most of the mines over the next half-century. **We cannot make this journey in an electric ferry without exposing the public to higher risk and cost than we need to.** These facts are clearly presented in Figure 3 and Table 28 of Glosten's Concept Design Report.

PSE has expressed an intent to generate little more than half of its electricity from renewables in the coming decades.[158] This decision leaves all of its customers complicit in an ongoing stream of greenhouse gas emissions. There remains sufficient potential to clean up our electrical grid that it is hard to justify connecting everything to it immediately as the best way to save the planet. **Dollar for dollar, regional energy conservation and renewable generation projects offer greater potential to cut greenhouse gas emissions than an electric Guemes ferry does—and with none of the risks to life and property. Because greenhouse gas emissions are ultimately a global problem, highly localized capital investment strategies can lead to very inefficient solutions—especially when those solutions pose as many expensive technical challenges as an electric Guemes ferry does.**

Electric cars are so admired today that it is easy to forget the long and winding road that brought us to this point in automotive history. The first electric car appeared in the late 1800s. In 1914, Henry Ford and Thomas Edison began collaborating on an electric car for the masses. The concept ultimately failed because of its low range and high cost—challenges that we are just beginning to overcome a century later with breakthroughs in battery technology.[159] Low range, high cost, and long charging times continued to doom a long procession of electric car debuts between now and then, especially in the 1970s and 2000s.[160,161] In November of 2019, the president of General Motors warned that range, cost, and charging are still the "three critical barriers" to the widespread adoption of electric cars.[162] The worldwide market penetration of electric cars recently surpassed 3%, and although many automakers are jumping onboard, analysts predict that the future growth of electric cars still relies on the continuation of favorable subsidies and regulations.[163]

The marine industry is still struggling with the "three critical barriers" that held back electric cars for a century: low range, high cost, and difficulties with charging. Although today's battery technology has become good enough for many automotive applications, it remains inadequate for almost all marine applications. The power penalties for weight and weather are far greater on the water than they are on land. The consequences of failures and fires are greater on the water too. Whereas cars are made by the thousands or millions after long design, development, and testing programs, most ferries are either one-offs or one of just a few hulls, built after a comparatively modest design effort. For these and other reasons, the maritime state of the art lags the automotive state of the art by untold decades.

If the marine industry could get closer to cracking the "three critical barriers," then there might be merit to dreaming about a wider role for electric vessels in a brighter, greener future. Yet I question whether dreaming is a mission that fits within the purview of a small, cash-strapped public works department operating Guemes Island's primary emergency response asset.

Appendix A: 28-car Cost Estimates

Publicly available cost estimates exist for all variants of the 32-car ferry, but only for the all-electric variant of the 28-car ferry. In order to compare the range of options for the 28-car ferry, I made approximate cost estimates based on the 32-car ferry using available resources. My cost estimates are not intended to serve as a formal basis for county decisions, but rather to gain a better understanding of the financial impact of the county's choice of propulsion system, given the size of ferry that the county now intends to build.

I estimated the capital and operating costs for the propulsion system of each 28-car variant (including associated shoreside infrastructure), as well as the total vessel capital cost and the total replacement program capital cost of each 28-car variant. These estimates are based on reports and memoranda released by Glosten in late 2017 and early 2018. I have assumed that costs are reported in late 2017 dollars, and I have made no adjustments for inflation in this section.

I separated the total capital cost of the 28-car ferry replacement program into four components:

1. The vessel capital cost of each variant's onboard systems related to propulsion and to supplying ship service loads (e.g. light, heat, etc.).
2. The vessel capital cost of the 28-car ferry without the aforementioned systems. I call this cost the "bareboat" cost, because it represents the remaining part of the vessel that is common to all variants, and therefore should have the same cost across all variants.
3. The shoreside capital cost that is related to propulsion (e.g. shoreside batteries, charging connections, etc.).
4. The shoreside capital cost that is not related to propulsion (e.g. dock and ramp modifications), which is the same for all variants.

Vessel and Propulsion System Capital Cost Estimates

My model of vessel capital cost is built on two reports, because the Engineer's Cost Estimate[164] does not isolate propulsion system capital costs, and the Concept Design Report,[6] released two weeks later, does not include total vessel capital costs. I back-calculated the "ex-propulsion bareboat" cost of the 32-car ferry by subtracting the cost estimates for onboard propulsion equipment in the Concept Design Report from the total vessel cost estimates in the Engineer's Cost Estimate. I had expected the resulting bareboat costs, presented in Exhibit 29, to be a consistent value, representing the common platform onto which the various propulsion systems were installed. Instead the ex-propulsion bareboat costs ranged from \$10.5mn to \$12.0mn, following a trend that increased with total vessel cost. This trend suggests that the Concept Design Report may have assumed lower propulsion system capital costs than the Engineer's Cost Estimate did.

I created Exhibit 30 to confirm this unexpected result. Exhibit 30 contrasts the relative differences in 32-car vessel capital costs as they are presented in the Concept Design Report and the Engineer's Cost Estimate. I started with the assumption that any cost difference between the vessel variants must be related to the propulsion system, because in every other respect, these variants are supposed to be identical. I calculated the difference in each variant's vessel capital cost relative to the baseline geared diesel vessel, because we need a common reference point for measuring cost, and the difference in cost is ultimately the measure of merit. For the Concept Design Report, I measured the difference in vessel propulsion system capital cost. For the Engineer's Cost Estimate, I measured the difference in vessel total capital cost. The capital cost differences published in the Concept Design Report are \$0.5mn to \$1.5mn lower than the capital cost differences published in the Engineer's Cost Estimate. A similar trend holds when shoreside propulsion costs are included. **If the Engineer's Cost Estimate is to be taken as the authoritative resource on cost, then the lifecycle cost comparison in the Concept Design Report (viz. Figure 3 in the Concept Design Report) may have understated the capital and lifecycle cost premiums that must be paid for all propulsion system options relative to the baseline geared diesel system.**

Exhibit 29. 32-car ferry ex-propulsion bareboat cost

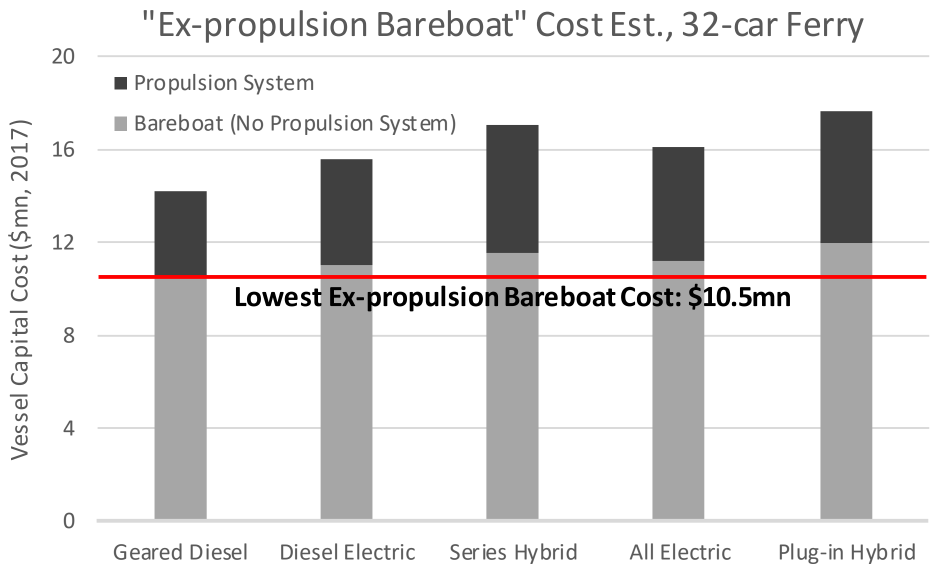
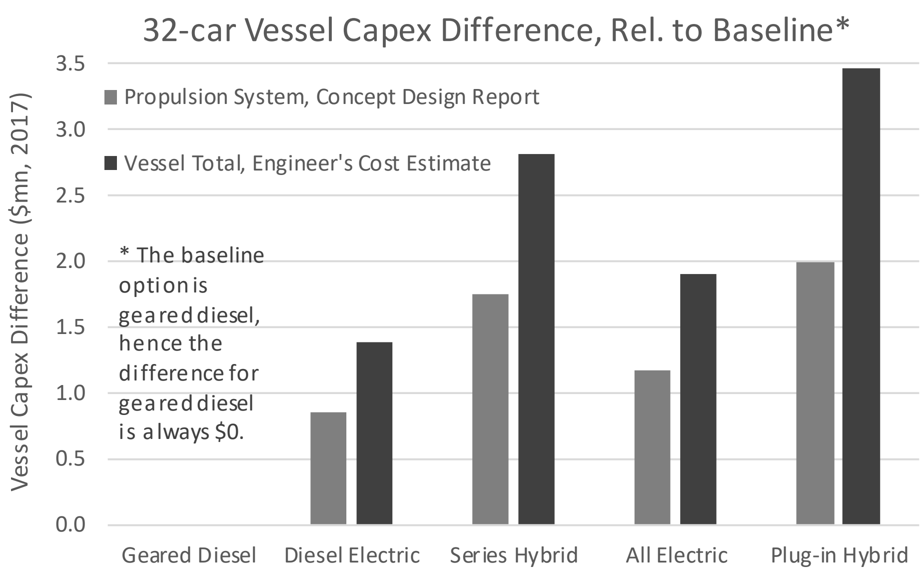


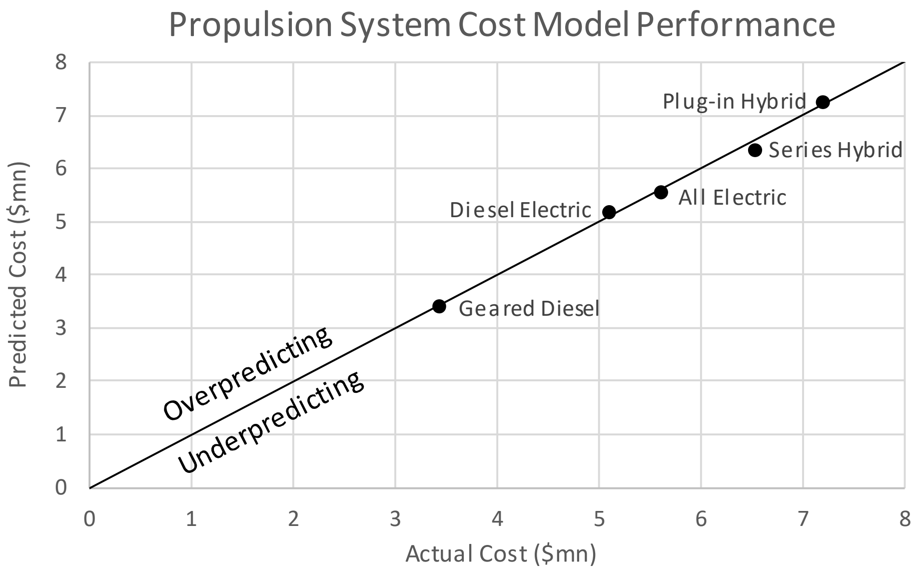
Exhibit 30. Differences in 32-car vessel capital cost estimates, relative to geared diesel



Based on Exhibit 29, the ex-propulsion bareboat cost is probably somewhere between $10.5mn and $12.0mn. I chose $10.5mn as the ex-propulsion bareboat cost, because it seems to be the lowest ex-propulsion bareboat cost that I could calculate, based on a reconciliation of the information jointly available in the Concept Design Report and the Engineer's Cost Estimate. By choosing the lowest available ex-propulsion bareboat cost, I have tried to reduce my chances of understating the capital costs of the different propulsion systems.

After trying a few methods of scaling propulsion capital costs for the 28-car ferry, I settled on a multivariable regression model parameterized by total installed diesel engine power, total installed propulsion motor power, and total installed battery energy. The adjusted correlation coefficient of the model is 0.978, and a prediction performance plot for the 32-car ferry is presented in Exhibit 31.

Exhibit 31. Propulsion system cost model prediction performance plot



Before creating this regression model for 28-car propulsion system capital cost, I adjusted the cost of the 32-car geared diesel propulsion system to reflect the lower engine cost schedule of EPA Tier 3 rather than Tier 4. The 28-car Options Cost Estimate[38] indicates that the smaller ferry's onboard battery capacity would be 24% smaller (800 kWh vs. 1,050 kWh at comparable design maturity). Assuming that these two battery banks were sized using the same methodology, and that the operational tempo (per Table 11 of the Concept Design Report) remains unchanged, then the decrease in onboard battery capacity would be directly proportional to the decrease in required power (i.e. energy is the product of power and time). A 24% power reduction implies that the geared diesel ferry's maximum continuous engine rating (MCR) could decrease from 1,000 hp (746 kW) for the 32-car ferry to 762 hp (568 kW) for the 28-car ferry. The nearest standard engine size that meets or exceeds this power requirement is the largest available EPA Tier 3 engine, with a MCR of 803 hp (599 kW). Estimates provided by Caterpillar suggest that the initial cost per unit of installed propulsion engine power is 34% lower for Tier 3 relative to Tier 4 at these power levels.[165] Applying this reduction factor to the $800k engine cost on page A-9 of the Concept Design Report, the propulsion system capital cost of the 32-car geared diesel ferry decreased by $274k, from $3.71mn to $3.44mn. This adjustment was only used to calculate the cost regression coefficients for the 28-car ferry's onboard systems, in order to reflect more accurately the cost of components when Tier 4 engines are not required.

In order to apply my cost regression to the full range of 28-car variants, I needed to establish the installed engine power, motor power, and battery energy of each variant. The only 28-car variant that exists in the public domain is the all-electric variant, so the properties of other variants had to be scaled from the properties of the 32-car variants. For the reason described in the previous paragraph, I used the ratio of 28-car to 32-car all-electric battery capacities as a basis for scaling down the three regression parameters for the 28-car variants. Assumed parameters are presented in Exhibit 32, including updated all-electric parameters to reflect the county's latest plan to pursue "the all-electric concept with a back-up generator on board for emergencies"[11] as it is presented as the "28-car limited" option in the 28-car Options Cost Estimate (which is the option that matches the cost announced in Skagit County's May 2019 newsletter[71]).

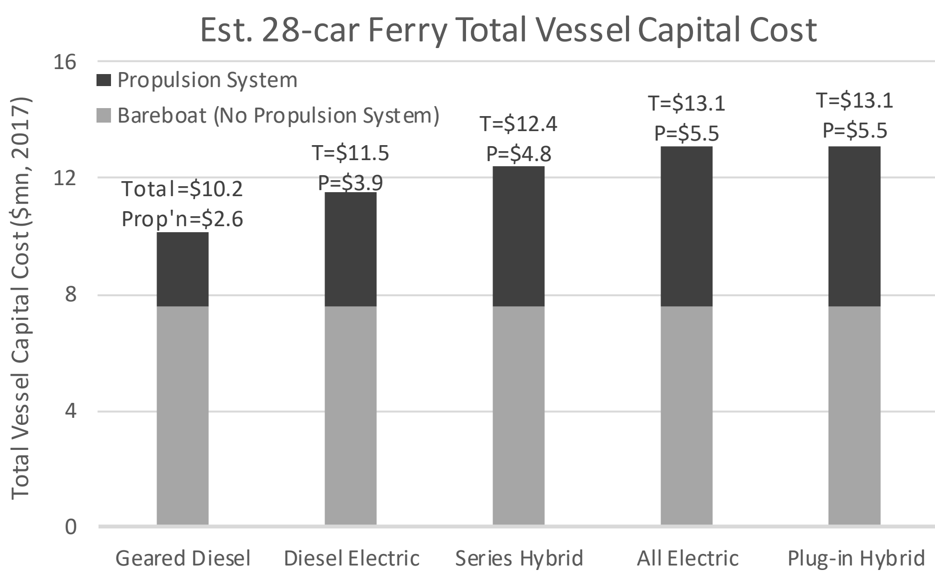
Exhibit 32. 28-car ferry assumed propulsion system parameters for cost regression

System	Engine Power[1] (kW)	Motor Power[2] (kW)	Battery Energy[3] (kWh)
Geared Diesel	1,240	0	0
Diesel Electric	1,260	1,160	0
Series Hybrid	1,260	1,160	230
All Electric	550	1,160	800
Plug-in Hybrid	840	1,160	650

[1] Engine power is total installed engine power, including generator sets, each rounded to the nearest 10 kW.
[2] Motor power is total installed propulsion motor power, each rounded to the nearest 10 kW.
[3] Battery energy is total battery capacity installed on the vessel, rounded to the nearest 10 kWh.

I back-calculated the bareboat cost of the 28-car ferry to be $7.6mn (28% lower than that of the 32-car ferry) by subtracting the regression-based propulsion system cost estimate from the total "28-car limited" vessel cost estimate in the 28-car Options Cost Estimate. I calculated the propulsion system costs of the other 28-car variants with the regression, and then I added them to the 28-car bareboat cost to get a set of 28-car vessel capital costs. Vessel capital costs are presented in Exhibit 33; they decreased between 19% and 29% across the range of variants relative to their 32-car counterparts. Estimated propulsion system capital costs are also called out in Exhibit 33. The vessel capital cost of the 28-car all-electric ferry matches the value published for the "28 Limited" variant in the 28-car Options Cost Estimate.

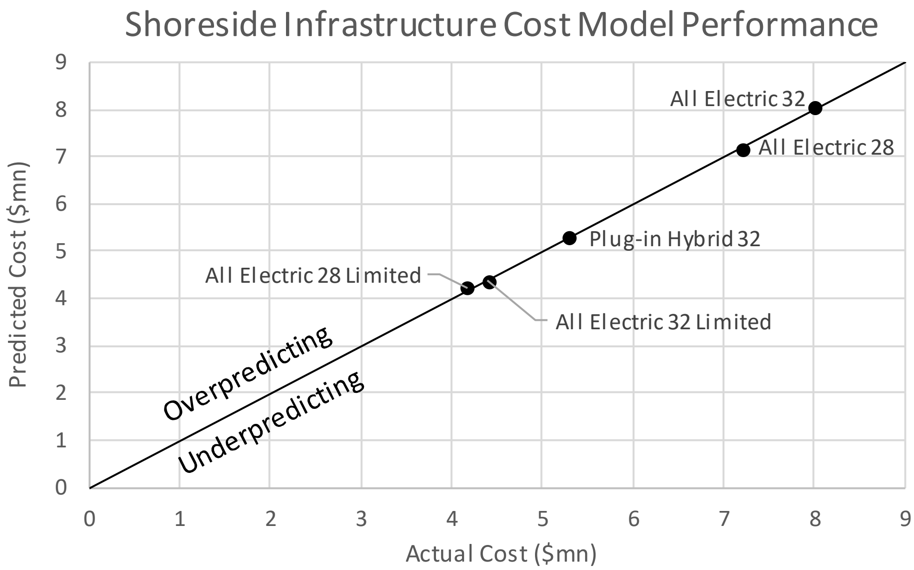
Exhibit 33. 28-car ferry total vessel capital cost estimates



Shoreside Capital Cost Estimates

Only the all-electric and plug-in hybrid ferries have capital costs related to shoreside propulsion equipment, and the all-electric ferry's shoreside capital costs are explicitly stated in the 28-car Options Cost Estimate (under "28-car limited," for reasons already explained). To estimate the cost of shoreside infrastructure for the 28-car plug-in hybrid, I created another multivariable regression based on all available cost estimates for shoreside electrical infrastructure for this project. The regression was parameterized by shore battery energy, shore connection power, and utility connection power. The adjusted correlation coefficient of the model is 0.999, and a prediction performance plot is presented in Exhibit 34. The regression accounts only for the cost to Skagit County. It does not include the portion of utility connection costs that Puget Sound Energy has agreed to absorb, as described in the 28-car Options Cost Estimate.

Exhibit 34. Shoreside infrastructure cost model prediction performance plot

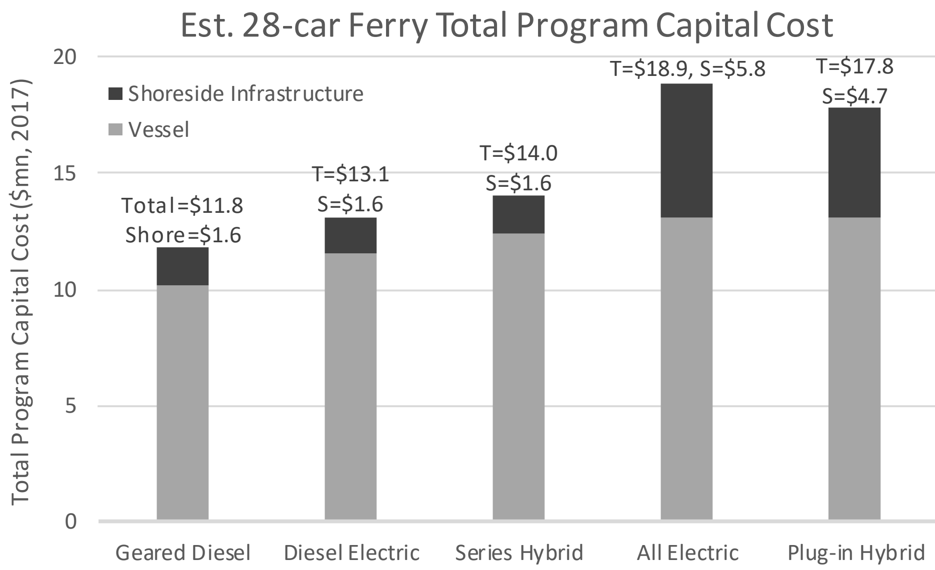


I scaled the shoreside infrastructure parameters of the 32-car plug-in hybrid ferry by the ratio of the shore parameters of the 32-car "limited" all-electric ferry to the 32-car original all-electric ferry. This approach resulted in a shore battery energy of 460 kWh, a shore connection power of 900 kW, and a utility connection power of 250 kW. With these assumptions, I estimated the shoreside electrical costs for the plug-in hybrid ferry to be $3.1mn using the regression. The $4.2mn shoreside electrical costs for the all-electric ferry were taken directly from the 28-car Options Cost Estimate.

Total Program Capital Cost Estimates

Total 28-car ferry replacement program capital cost estimates are presented in Exhibit 35. These cost estimates include the capital costs of the vessel plus all of the proposed shoreside infrastructure upgrades discussed in Glosten's formal cost estimates. The total program capital cost for the 28-car all-electric ferry matches the value published for the "28 Limited" variant in the 28-car Options Cost Estimate.

Exhibit 35. Total 28-car ferry replacement program capital cost estimates



Operating Cost Estimates

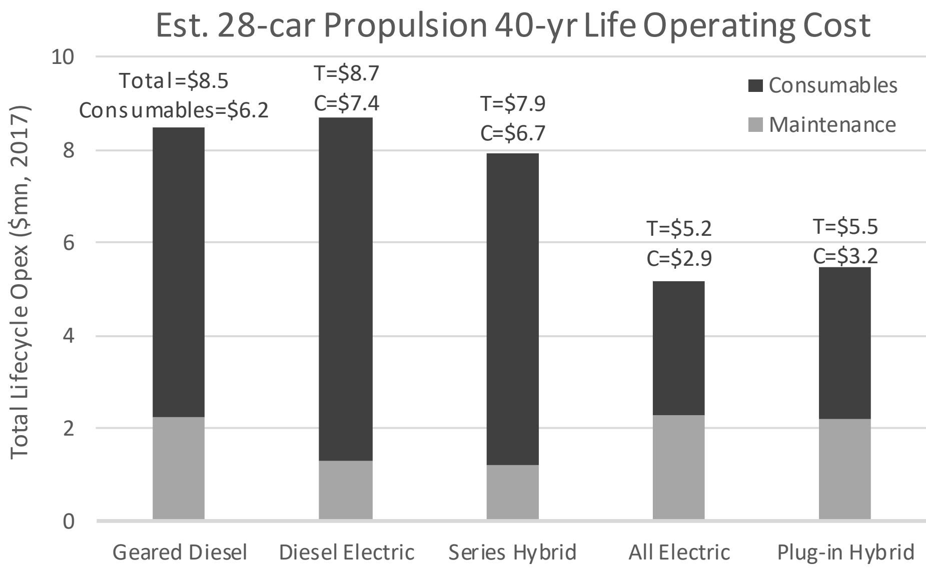
I scaled the costs of consumables (e.g. electricity, fuel, lubricants) from the numbers reported for the 32-car ferry in the Concept Design Report as a function of installed power, with the idea that the energy consumed is directly proportional to the energy capacity of the battery bank, for reasons previously described. There were four exceptions to this scaling regime:

1. I set diesel exhaust fluid (DEF) consumption to zero, because it is not needed with an EPA Tier 3 engine.
2. I increased total fuel consumption for the geared diesel system by 3.9% to reflect the reduced fuel efficiency of Caterpillar EPA Tier 3 engines relative to Tier 4 engines. I collected fuel consumption data for Tier 4 engines from page A-3 of the Concept Design Report, and for Tier 3 engines from a C18 fuel consumption curve provided by Caterpillar.[166] I weighted fuel consumption changes by engine power level, according to the time spent at each power level, per Table 12 in the Concept Design Report.
3. The Concept Design Report seemed to have assumed zero diesel consumption for the all-electric ferry, whereas the county presently expects diesel to make up 1% of total energy consumption (lubricants seem to have been accounted for).[49] I added 1% of diesel costs from the series hybrid ferry (assuming similar efficiency in diesel mode), and I subtracted 1% of electricity costs.
4. In light of the substantially reduced battery and charging capacity of the 28-car plug-in hybrid, I assumed 10% diesel dependence and 90% electricity dependence per the method explained in exception #3 above, with 10% of the series hybrid ferry's lubricant consumption.

I scaled the cost of maintenance and repowers from the numbers reported for the 32-car ferry in the Concept Design Report by the ratio of each propulsion system variant's 28-car capital cost to 32-car capital cost.

Total 40-year propulsion lifecycle operating cost estimates are presented in Exhibit 36. Operating costs decreased between 24% and 27% across the range of options relative to the 32-car variants.

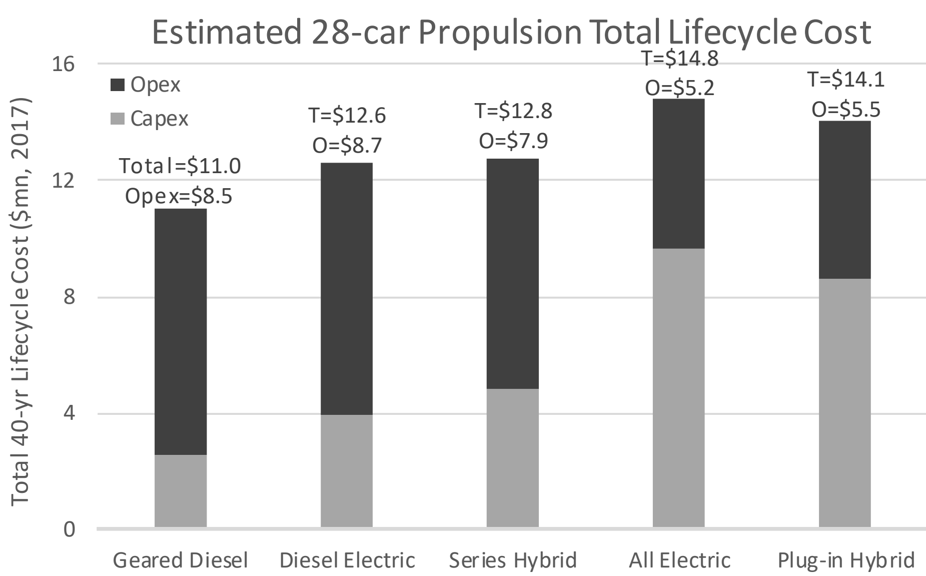
Exhibit 36. 28-car ferry propulsion system 40-year lifetime operating cost estimates



Propulsion Lifecycle Cost Estimates

To complete the picture, I calculated total propulsion system lifecycle costs as the sum of capital and lifetime operating costs, including propulsion-specific shoreside infrastructure costs. The results are presented in Exhibit 37. Glosten's propulsion lifecycle cost estimates assumed a residual value of $0 and a disposal cost of $0 at the end of the 40-year analysis period. I have maintained those assumptions.

Exhibit 37. 28-car ferry propulsion system total lifecycle cost estimates



Appendix B: Replacement Plan Cost Calculations

In late 2013, Skagit County released the Guemes Island Ferry Replacement Plan,[73] which stated on its second page that we could save millions of dollars by building a new ferry immediately rather than refurbishing the existing ferry. The Replacement Plan's conclusions were based on a parametric estimate that a simple 26-car ferry would cost $8.4mn to build. In late 2017, after developing a larger concept design with more amenities, Skagit County released an Engineer's Cost Estimate[167] that placed the cost of a new 32-car ferry and its required infrastructure between $15.8mn (for a diesel boat) and $25.7mn (for an all-electric boat). When the price of the new ferry doubles or triples, is new construction still more cost-effective than a refit?

Lifecycle Cost Estimation Methods

Lifecycle cost is the total net cost to acquire, to use, and to discard an asset, over some fixed period of time, expressed as one single cost in today's dollars. Because all relevant financial differences can be accounted for in a lifecycle cost estimate, lifecycle cost is frequently used to select the most economically efficient course of action from a diverse set of options.

The National Institute for Standards and Technology (NIST, of the Department of Commerce) collaborated with the Federal Energy Management Program (FEMP, of the Department of Energy) to publish a method for lifecycle cost estimation in Handbook 135.[79] Handbook 135 was developed to evaluate the cost of conservation and renewable projects in all federal buildings, although it is used much more widely, including in the marine industry. The propulsion lifecycle cost analysis in the Concept Design Report cites the NIST FEMP methodology.[168]

The methodology in Handbook 135 aims to provide a thorough accounting of costs over a finite period of time, in order to make it possible to compare the costs of a wide range of options on equal footing. Some of the key concepts from Handbook 135 that relate to our project are below:

- **<u>Discount rate.</u>** The discount rate is the annual rate at which a dollar in the future becomes less valuable than a dollar in the present. A dollar in the present is generally more valuable (or more expensive) than a dollar in the future, because inflation erodes the value of a dollar over time, and because every dollar spent in the present is a missed opportunity to invest in some other asset that pays a higher return. This rationale also holds true in Skagit County's situation, where they have no money to invest and instead are borrowing money:[88] the more they borrow, the greater their negative return through interest payments, and the more county revenue must be diverted from other programs to pay off ferry debt.
- **<u>Investment costs.</u>** Handbook 135 uses the term "investment costs" for financial transactions related to major project components and their integration, such as:
    - Capital costs to plan, design, acquire, install, and commission the project. Capital costs also include "capital replacement" projects, such as the planned replacement of major components.
    - The residual value of the project at the end of the analysis period. The residual value is the value of the project's assets in place; it is usually money going in rather than money going out, even though it is listed as a "cost" in Handbook 135. If your house has a somewhat new furnace in good condition, its residual value may be fairly high, because you could continue using it well into the future. If your house has a broken furnace that needs to be replaced, it may have a negative residual value, because you might have to pay somebody to haul it away (Handbook 135 treats disposal costs as negative residual values).

- **Operational costs.** Handbook 135 uses the term "operational costs" for financial transactions that occur (and often recur) over the course of the project's life, as a function of the capital assets performing their duties. Examples of operational costs include:
  - Energy and other consumables: e.g. diesel, electricity, and lubricants.
  - Routine operation, maintenance, and repair:[169] e.g. personnel, paint, and haulouts. Costs that are constant over the range of options, e.g. a fixed number of crew, can be omitted from the comparison—as long as they are not forgotten in the budget.
  - Revenues. Revenues are money going in, even though they are listed under "costs" in Handbook 135. Ferries of different sizes might generate different revenues, which could affect the net lifecycle cost.

The Ferry Replacement Plan: As Released

Tables 10 through 12 of the Replacement Plan, reproduced below in Exhibit 38, summarize the lifecycle cost calculations on which that report's conclusions were based. The three options studied in the Replacement Plan, and their corresponding table numbers in that report, are as follows:

- Option A: replace *Guemes* immediately (Replacement Plan (R.P.) Table 10).
- Option B: perform a minor refit on *Guemes* and replace it in 10 years (R.P. Table 11).
- Option C: perform a major refit on *Guemes* and replace it in 18 years (R.P. Table 12).

Exhibit 38. Tables 10-12 as they were presented in the Ferry Replacement Plan

Table 10: Option A Cost Breakdown

Cost	Existing Vessel	Replacement Vessel	Total
New Construction	-	$8,400,000	$8,400,000
Annual Maintenance	$717,000	$3,156,000	$3,873,000
Fuel & Lube Oil	$822,000	$6,440,000	$7,262,000
		23-Year Total	**$19,535,000**

Table 11: Option B Cost Breakdown

Cost	Existing Vessel	Leased Vessel	Replacement Vessel	Total
Overhaul	$929,000	-	-	$929,000
Lease	-	$1,095,000	-	$1,095,000
New Construction	-	-	$8,400,000	$8,400,000
Annual Maintenance	$2,295,000	-	$1,854,000	$4,149,000
Fuel & Lube Oil	$2,466,000	$274,000	$4,186,000	$6,926,000
			23-Year Total	**$21,499,000**

Table 12: Option C Cost Breakdown

Cost	Existing Vessel	Leased Vessel	Replacement Vessel	Total
Overhaul	$4,794,000	-	-	$4,794,000
Lease	-	$1,095,000	-	$1,095,000
New Construction	-	-	$8,400,000	$8,400,000
Annual Maintenance	$4,622,000	-	$564,000	$5,186,000
Fuel & Lube Oil	$5,378,000	$274,000	$1,610,000	$7,262,000
			23-Year Total	**$26,737,000**

Appendix E of the Replacement Plan contains more detailed cost estimation tables for Options A through C. Those tables are more complicated, and also more challenging to reconcile with the body of the Replacement Plan, because they include more nuances. I have chosen to focus on Tables 10-12, because the costs discussed in the body of the Replacement Plan—where the key conclusions are reached—seem to match those tables.

The tables in Exhibit 38 show the presence of some elements I emphasized from Handbook 135, such as capital costs, energy, consumables, and maintenance. However, they also appear to be missing some important elements from Handbook 135, such as discount rate and residual value. In the following subsections, I will draw attention to some assumptions and decisions that might change the outcome of the Ferry Replacement Plan if that report were to be revised.

Discount Rate

At Skagit County's request, the Replacement Plan did not account for the time value of money.[80] As a result, the cost of a new ferry is always the same in present dollars, regardless of whether it is built right away or 18 years later. This is a nonstandard practice, because it ignores the opportunity costs that can be avoided when a major investment is postponed. If we apply the 3% discount rate used in the Concept Design Report, the money spent on a new ferry 18 years in the future is 41% cheaper than the money spent on a new ferry today.[170]

The county's latest ferry acquisition strategy is especially sensitive to the discount rate, because it involves securing a large loan now and repaying it over decades using a trickle of grants and surcharges. If we buy a new ferry today, we need to borrow almost the entire balance upfront, because "Skagit County does not currently have funds that are allocated for vessel replacement,"[2] and the CRAB grant is paid in annual installments of no more than $500k over a period of up to 20 years.[72] If instead we wait 10 or 18 years to build a new ferry, then we could tap our accrued replacement fund (surcharge income plus CRAB income plus interest income)[82] and borrow much less money, thereby reducing our borrowing costs. These circumstances make tomorrow's dollars cheaper than today's dollars. We would still need to spend a smaller sum of today's dollars on a refit, which works against the money saved by postponing new construction. This tradeoff would be accounted for in an updated lifecycle cost analysis that uses a discount rate, such that the lowest-cost path would become evident.

The discount rate also becomes more important now that the county intends to invest in cutting-edge propulsion technology. Cutting-edge technologies often get cheaper, better, and more reliable in the decades after their debut (e.g. flat-panel televisions). The Concept Design Report assumes that the capital cost of batteries will decrease by 2% every year relative to all other components.[81] If this prediction comes true, then the batteries bought in 18 years would be 30% cheaper than the batteries bought today.[171] A more stable and reliable technology would also be less prone to premature failures and the costs associated with remediation.

Operational Costs

We have seen from the Concept Design Report that the five propulsion systems under consideration have a wide range of operational costs. It is worth revising operational costs to reflect our new and more detailed knowledge about the range of costs associated with propulsion.

Revenues

Relative to the existing ferry, the post-refit lengthened 26-car ferry (Option C) and the new 28- and 32-car ferries (Option A) have the potential to carry more vehicles during peak times, and to induce additional demand year-round, so they might have slightly higher annual revenues. Revenue forecasting is a bit complicated, but a rudimentary estimate could be made.

Capital Cost

The estimated capital cost of the ferry replacement program is substantially higher now than it was when the Replacement Plan was released. Large changes in capital cost can have a major impact on the outcome of a lifecycle cost analysis. It may also be worth refining the capital cost estimates for refitting the existing ferry, to ensure that all of the latest information is taken into account at a similar level of detail.

In the timeline of the three replacement scenarios, there is an 18-year gap between the earliest ferry replacement in Option A and the most postponed ferry replacement in Option C. In ferry years, that is half a lifetime.[172] It is worth asking whether we would build different-size ferries (with different associated costs) in those two scenarios, given the county's demand forecasts.[173]

Residual Value

At Skagit County's request, the Replacement Plan did not account for the residual values of assets.[80] This exclusion has significant potential to distort the outcome of the study. NIST Handbook 135 explains the importance of accounting for residual value when the capital investment options occur at different points over a fixed analysis period:

> **The residual value estimate for a capital replacement, needed to extend the life of an alternative to the length of a common study period, may also be a critical factor in the LCCA [lifecycle cost analysis] and thus care should be given in estimating this value.**[174]

An asset's value, age, and utility are often closely related. New ferries are more valuable than old ferries because they are capable of operating farther into the future, thereby postponing the next expensive refit or replacement. Age is the main reason cited for replacing the existing ferry immediately. Someday, age will be the main reason cited for replacing the ferry that we have not yet built. Because this problem goes on forever, the age of the ferry at the end of each scenario matters a great deal. Consider the timetables in Figures 10 through 12 of the Replacement Plan. We end up with very different ferry ages at the end of the same analysis period:

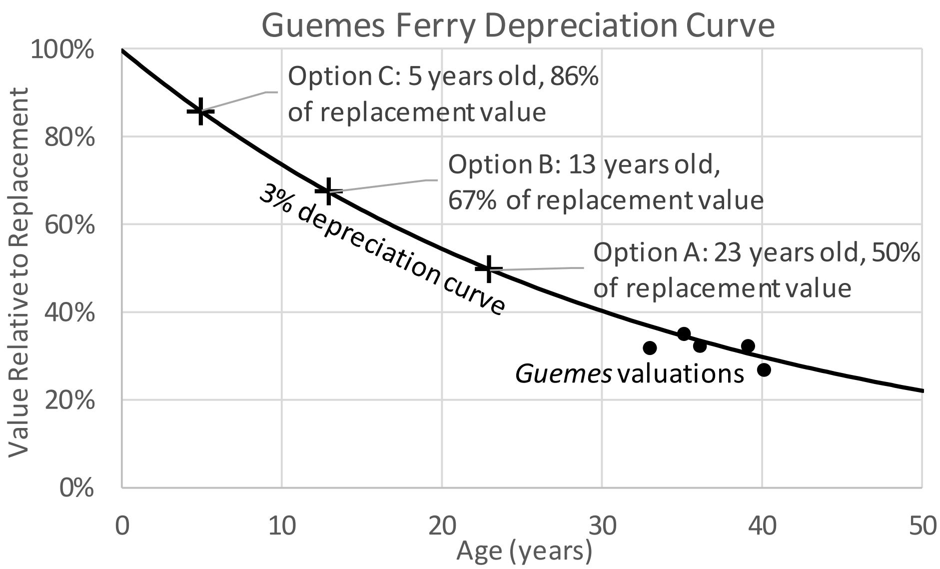
- In Option A, immediate replacement, the new ferry is 23 years old at the end.
- In Option B, minor refit of *Guemes*, the new ferry is 13 years old at the end.
- In Option C, major refit of *Guemes*, the new ferry is 5 years old at the end.

Exhibit 39 shows an estimated depreciation curve for the existing Guemes ferry, based on five publicly available valuation survey reports.[175] On average, for every year that the ferry has aged (horizontal axis), it has lost 3% of its value (compounded annually, rounded to the nearest whole percent) relative to the value of an identical new ferry (vertical axis). According to the survey reports, *Guemes* has been very well maintained, leading to less depreciation than is typical for ships.[176] Let us assume that the new ferry will depreciate in the same way as the existing ferry. At the end of the Replacement Plan's analysis period, the ferry in Option C (replace in 18 years) will have lost 14% of its value, whereas the ferry in Option A (replace immediately) will have lost 50% of its value.

The consequence of excluding residual value is that the Replacement Plan accounts only for what we pay, not for what we get. Since new ferry costs are identical in all three scenarios (because no discount rate is applied), since and operational costs are very similar in all three scenarios, the automatic low-cost option is the scenario with the lowest capital cost. The scenario with the lowest capital cost is the one that does not "waste money" on refitting the existing ferry. We could write in a billion dollars as the new ferry's capital cost, and we would still conclude that Skagit County would save money by immediately building a new billion-dollar ferry, rather than refitting the existing ferry for $6mn, because we would save $6mn.

Hopefully this conclusion troubles you. If you own a car, you know instinctively that there should be a crossover point in your decision to replace it. There is some price for a new car above which you would rather maintain the car you have now, even if those maintenance costs eventually add up to more than its Blue Book value. When you make that decision, you weigh the cost of each option against the utility of each option. The Replacement Plan as-released has no crossover point because it accounts only for cost, not for utility.

Exhibit 39. Guemes ferry estimated depreciation curve



The Ferry Replacement Plan: As Revised by Me

In order to create a lifecycle cost analysis with crossover points, I added a line item for residual value in Tables 10-12 of the Replacement Plan, as is shown in Exhibit 40 on the following page. A salvage value of $40k is included for the existing ferry, per the 2019 valuation survey,[177] and the residual value of the new ferry is depreciated by 3% per year relative to its replacement cost, per Exhibit 39. All other assumptions and methods in the Replacement Plan remain unchanged.

Note how the replacement ferry's residual value in Exhibit 40 increases From Table 10 to 11 and from Table 11 to 12, as it becomes progressively younger at the end of the analysis period. Option A (immediate replacement) is still the lowest-cost option, but the cost of Option B (minor refit) is now very close.

To illustrate the effect of having a crossover point, I arbitrarily doubled the cost of the replacement ferry, from $8.4mn to $16.8mn, in Exhibit 41, two pages hence. Because we have spent twice as much money on a depreciating asset, we also lose twice as much money over the same period of ownership, as the formerly new asset gets closer to needing its own expensive refit or replacement. In Exhibit 41, Option B (minor refit) is now decisively the lowest-cost option. **Even though the existing ferry requires more investment relative to its residual value, its refurbishment now seems like a favorable investment, because the alternative is to buy a very expensive new boat. This is the paradox we face as owners of a 40-year-old ferry: even though it sometimes seems costly to own, a larger and more sophisticated ferry could be even costlier to own in absolute terms.**

Exhibit 42, also two pages hence, shows the total program cost trends (vertical axis) that emerge when we vary the cost of the replacement ferry (horizontal axis) continuously over a wide range, account for residual value, and leave all other assumptions and methods in the Replacement Plan unchanged. **Below $11mn for a new ferry, Option A (immediate replacement) minimizes the county's expenses. Between $11mn and $28mn for a new ferry, Option B (minor refit) minimizes the county's expenses. Above $28mn for a new ferry, Option C (major refit) minimizes the county's expenses.** This progression of crossover points makes sense intuitively: the higher the price of a new vehicle, the greater your incentive to continue using your existing vehicle.

Exhibit 40. Tables 10-12 for a replacement cost of $8.4mn, with residual value included

Ferry Replacement Plan Table 10: Option A: New Ferry Immediately (costs in $mn)				
Costs in present $mm	Existing Vessel	Leased Vessel	Replacement Vessel	Total
Overhaul	0.00	0.00	0.00	0.00
Lease	0.00	0.00	0.00	0.00
New Construction	0.00	0.00	8.40	8.40
Annual Maintenance	0.72	0.00	3.16	3.87
Fuel & Lube Oil	0.82	0.00	6.44	7.26
Residual Value	-0.04	0.00	-4.17	-4.21
Subtotals	1.50	0.00	13.83	15.33
Total, with replacement ferry 23 years old at end of evaluation period:				**15.33**

Ferry Replacement Plan Table 11: Option B: Minor Refit & Replace in 10 Years (costs in $mn)				
Costs in present $mm	Existing Vessel	Leased Vessel	Replacement Vessel	Total
Overhaul	0.93	0.00	0.00	0.93
Lease	0.00	1.10	0.00	1.10
New Construction	0.00	0.00	8.40	8.40
Annual Maintenance	2.30	0.00	1.85	4.15
Fuel & Lube Oil	2.47	0.27	4.19	6.93
Residual Value	-0.04	0.00	-5.65	-5.69
Subtotals	5.65	1.37	8.79	15.81
Total, with replacement ferry 13 years old at end of evaluation period:				**15.81**

Ferry Replacement Plan Table 12: Option C: Major Refit & Replace in 18 Years (costs in $mn)				
Costs in present $mm	Existing Vessel	Leased Vessel	Replacement Vessel	Total
Overhaul	4.79	0.00	0.00	4.79
Lease	0.00	1.10	0.00	1.10
New Construction	0.00	0.00	8.40	8.40
Annual Maintenance	4.62	0.00	0.56	5.19
Fuel & Lube Oil	5.38	0.27	1.61	7.26
Residual Value	-0.04	0.00	-7.21	-7.25
Subtotals	14.75	1.37	3.36	19.48
Total, with replacement ferry 5 years old at end of evaluation period:				**19.48**

The financial aspects of today's ferry replacement process have changed a great deal since we first analyzed the idea in 2013. The crossover points in Exhibit 42 might shift significantly if all of the methodological modifications discussed in this appendix were taken into account. From a standpoint of reducing financial risk, I think it would be worth the effort to refine our lifecycle cost comparison so that it follows a recognized standard such as NIST Handbook 135, and to represent today's more developed knowledge about our options and their costs.

We could reduce financial risk by following pragmatic, established accounting practices. We could also reduce financial risk by accounting for the disparate capital and operational costs unleashed by a range of propulsion options that we had not envisioned, and a ferry size and cost that is greater than the one we had considered, when the Replacement Plan was written.

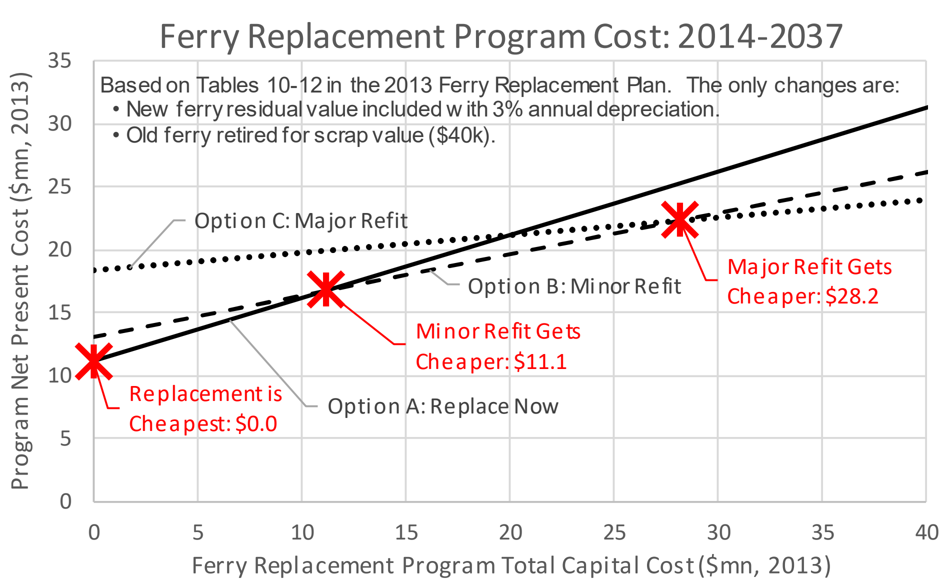
Exhibit 41. Tables 10-12 for a replacement cost of $16.8mn, with residual value included

Ferry Replacement Plan Table 10: Option A: New Ferry Immediately (costs in $mn)				
Costs in present $mm	Existing Vessel	Leased Vessel	Replacement Vessel	Total
Overhaul	0.00	0.00	0.00	0.00
Lease	0.00	0.00	0.00	0.00
New Construction	0.00	0.00	16.80	16.80
Annual Maintenance	0.72	0.00	3.16	3.87
Fuel & Lube Oil	0.82	0.00	6.44	7.26
Residual Value	-0.04	0.00	-8.34	-8.38
Subtotals	1.50	0.00	18.06	19.56
Total, with replacement ferry 23 years old at end of evaluation period:				**19.56**

Ferry Replacement Plan Table 11: Option B: Minor Refit & Replace in 10 Years (costs in $mn)				
Costs in present $mm	Existing Vessel	Leased Vessel	Replacement Vessel	Total
Overhaul	0.93	0.00	0.00	0.93
Lease	0.00	1.10	0.00	1.10
New Construction	0.00	0.00	16.80	16.80
Annual Maintenance	2.30	0.00	1.85	4.15
Fuel & Lube Oil	2.47	0.27	4.19	6.93
Residual Value	-0.04	0.00	-11.31	-11.35
Subtotals	5.65	1.37	11.53	18.55
Total, with replacement ferry 13 years old at end of evaluation period:				**18.55**

Ferry Replacement Plan Table 12: Option C: Major Refit & Replace in 18 Years (costs in $mn)				
Costs in present $mm	Existing Vessel	Leased Vessel	Replacement Vessel	Total
Overhaul	4.79	0.00	0.00	4.79
Lease	0.00	1.10	0.00	1.10
New Construction	0.00	0.00	16.80	16.80
Annual Maintenance	4.62	0.00	0.56	5.19
Fuel & Lube Oil	5.38	0.27	1.61	7.26
Residual Value	-0.04	0.00	-14.43	-14.47
Subtotals	14.75	1.37	4.55	20.67
Total, with replacement ferry 5 years old at end of evaluation period:				**20.67**

Exhibit 42. Ferry replacement program sensitivity to replacement ferry capital cost



Appendix C: Lifecycle Cost Spread Illustration

Every choice comes with risk—that is, with a unique set of possibilities and consequences. We do our best to minimize the possibilities and consequences of bad outcomes, yet we know that they cannot be eliminated. In order to illustrate how risk can print through to financial outcomes, I created two hypothetical probability distributions to represent the lifecycle cost outcomes of two projects:

- Project D: a low-cost, low-risk project, such as one that uses established technology. This project is conceptually similar to a geared diesel propulsion system, for which lifecycle costs are low and outcomes are somewhat predictable.
- Project E: a high-cost, high-risk project, such as one that uses cutting-edge technology. This project is conceptually similar to an all-electric propulsion system, for which lifecycle costs are high and outcomes are somewhat unpredictable.

I used a beta distribution to model the cost outcomes, by way of a methodology that was developed by the U.S. Department of Defense for estimating the time and money that it takes to execute various projects.[178] The beta distribution is a two-parameter distribution that can be symmetrical or skewed. Beta distributions for cost generally skew to the right, because the lower limit on cost is usually more tightly defined than the upper limit on cost is. The modal (most probable) value in the distribution is usually the nominal cost estimate.

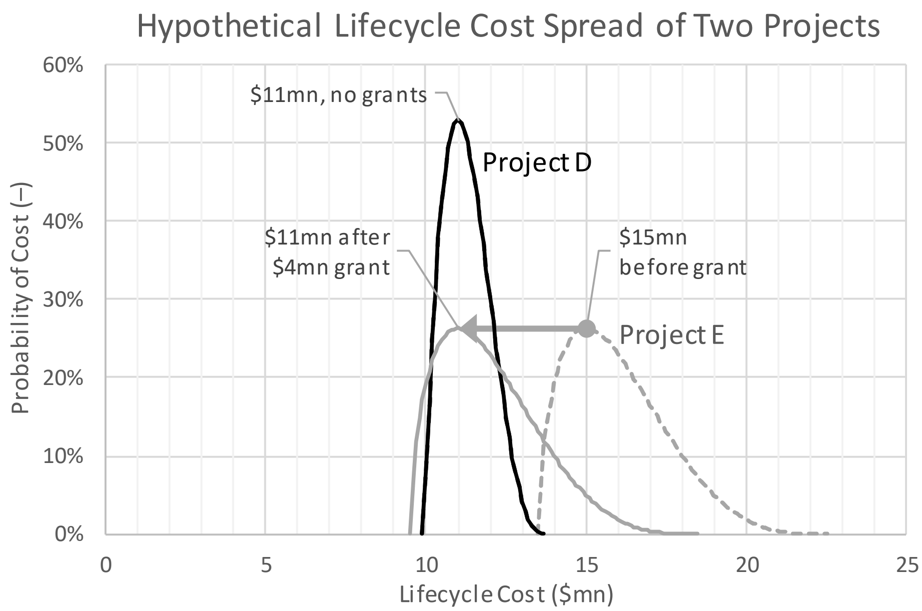
Exhibit 43 presents the assumptions that led to the cost probability distributions for Projects D and E. Since these distributions are hypothetical in nature, I made some arbitrary assumptions regarding the extent and probability of cost outcomes. My primary goal was to illustrate how a project with higher cost, as well as higher uncertainty, has a much greater risk of large cost overruns.

Exhibit 43. Properties of conceptual beta distributions for the lifecycle costs of two projects

	Project D		**Project E**	
	Modal Cost = $11mn Before Grants		Modal Cost = $15mn Before Grants	
	Factor on Modal Cost	Percentile	Factor on Modal Cost	Percentile
Minimum Cost	0.900	0%	0.900	0%
“Optimistic” Cost	0.950	12%	0.950	11%
“Most Likely” Cost	1.000	39%	1.000	30%
“Pessimistic” Cost	1.125	93%	1.250	94%
Maximum Cost	1.250	100%	1.500	100%

Exhibit 44 illustrates the lifecycle cost distributions for Project D and Project E. Hypothetical Project D has a lifecycle cost of $11mn and receives no grants, similar to the geared diesel propulsion system. Hypothetical Project E has a lifecycle cost of $15mn, similar to the all-electric propulsion system. In this hypothetical situation, Project E receives a $4mn grant so that it has the same modal (nominal) cost estimate as Project D does: $11mn. However, the cost distributions are based on the cost before grants, because the total project cost is the basis for cost variability. This is why the distribution for Project E is calculated at the $15mn price and then shifted $4mn to the left to represent the grant.

Exhibit 44. Hypothetical lifecycle cost spreads for Projects D and E



After Project E's leftward shift from the $4mn grant, the two projects have the same modal (nominal) cost estimate of $11mn. Yet the shapes of the two probability distributions are strikingly different. Project D has a narrower distribution that is more tightly clustered around the modal cost. Project E has a broader distribution that spreads much farther away from the modal cost, especially to the right, where costs are high. Where the two curves overlap, either project has a possibility of being more cost-effective, but not with equal probability. The probability that the actual cost falls between $10mn and $12mn is 83% for Project D, whereas it is only 49% for Project E. Most of Project E's remaining cost probability is on the right side of the graph, where costs are high. And Project E's curve spreads much farther to the right than Project D's curve does. **Taken together, Project E poses a much higher risk of much higher cost overruns, even though it has the same nominal cost estimate that Project D does after grants are taken into account.** The extent of this risk only becomes apparent when we look beyond the nominal cost estimates.

In public works and small regional government, a conservative attitude toward risk generally biases decision-makers toward the option with the most predictable outcome and the least chance of producing unlikely but extreme outcomes (i.e. reducing "tail risk"). This approach to risk is much better served by the shape of Project D's probability distribution.

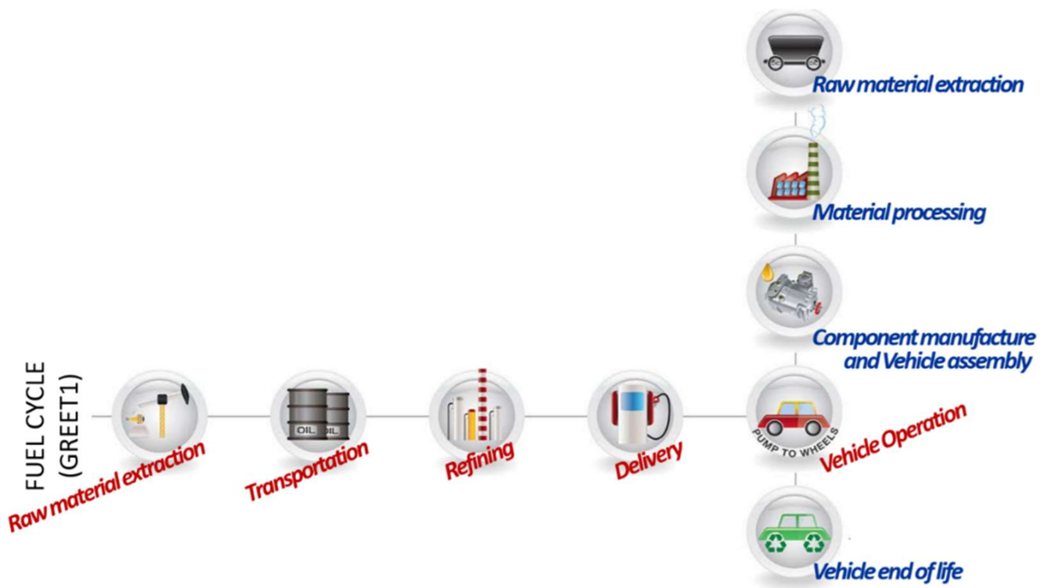
Appendix D: Airborne CO_2 Emissions Calculations

According to Skagit County's ferry replacement website, "an all-electric vessel would potentially… reduce harmful CO_2 (carbon dioxide) air emissions by 619,359 kg" per year.[112] Although I have not been able to trace this number to a source, it seems to describe the amount of CO_2 released from the existing ferry's exhaust stacks.[113]

A reduction in local air pollution would be a good outcome for the neighborhood, but it leaves many important questions unanswered. How environmentally damaging is our electricity supply? Or the supply chains that support the production and consumption of diesel and electricity? What is the environmental impact of building a new electric ferry, versus building a new diesel ferry, versus upgrading an existing diesel ferry? What is the impact of each ferry's upkeep and disposal?

A parallel set of questions in the automotive industry has attracted much professional scholarship, most notably at Argonne National Laboratories (ANL). ANL's lifecycle analysis method (Exhibit 45) examines a range of factors that affect a vehicle's overall environmental impact, including its manufacture, operation, and disposal.[179] The vertical line traces the vehicle's story, and the horizontal line traces the fuel's story.

Exhibit 45. ANL vehicle lifecycle analysis flowchart



Method

I took what I saw as the next logical step toward examining the bigger picture: CO_2 emissions from the powerplants feeding the electric ferry. That way, we could compare the impact of the fossil fuels being burned to power the ferry. This is just one of many additional steps that would be needed to get a clear picture of the environmental tradeoffs between diesel-burning engines and grid-charged batteries.

Skagit County is presently pursuing "the all-electric concept with a back-up generator on board for emergencies."[11] I compiled details for the all-electric ferry from the Concept Design Report (CDR)[6] and the 28-car Options Cost Estimate,[38] scaling figures from the 32-car ferry where published numbers were not available for the 28-car ferry. Based on a reported 24% decrease in battery capacity, I estimated that the 28-car ferry would have 800 hp (597 kW) of propulsion power installed at each end (refer to Appendix A for more information). I estimated that an average round trip would consume 110 kWh of energy at the propeller shaft and 16 kWh of energy at ship service loads (e.g. pumps, fans, heaters, and lights), before accounting for system efficiencies.

To compare the amount of CO_2 released by the hybrid and diesel propulsion options, we need to define two parameters for each system:

1. **System efficiency:** What percent of total released energy reaches the propeller or loads?
2. **Emissions rate:** How much CO_2 is released per unit of energy released?

With this information, I calculated emissions in the following way, starting from the energy consumed at the propeller shaft or ship service load:

$$\text{Emissions} = \frac{\text{Energy Consumed}}{\text{System Efficiency}} \times \text{Emissions Rate}$$

System Efficiency

In this appendix, I define system efficiency as the fraction of energy that is successfully transmitted from the electric powerplant or diesel engine either to the propeller shaft or to the circuits for ship service loads. My sources for component efficiencies are the Concept Design Report, a major electric propulsion equipment manufacturer,[180] the Environmental Protection Agency (EPA),[181] and the Energy Information Administration (EIA).[182]

Exhibit 46 shows the arrangement of the geared diesel system, with the trail of assumed equipment efficiencies and the calculated overall system efficiencies. The overall system efficiency is estimated to be 93% for propulsion loads and 94% for ship service loads.

Exhibit 46. System efficiency diagrams for geared diesel propulsion

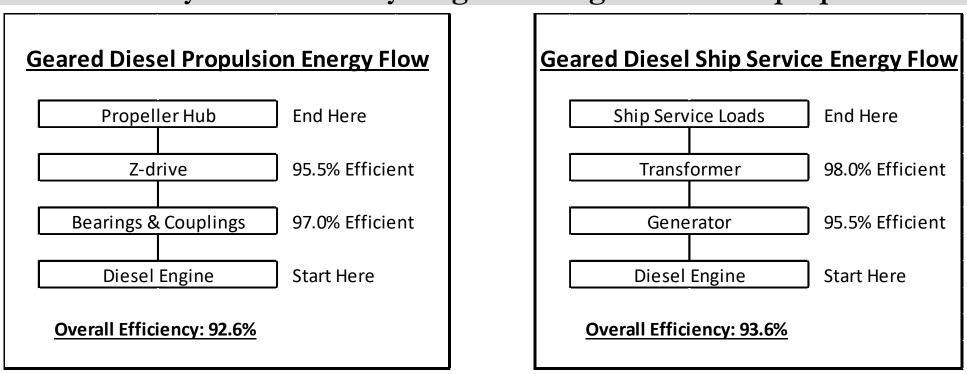
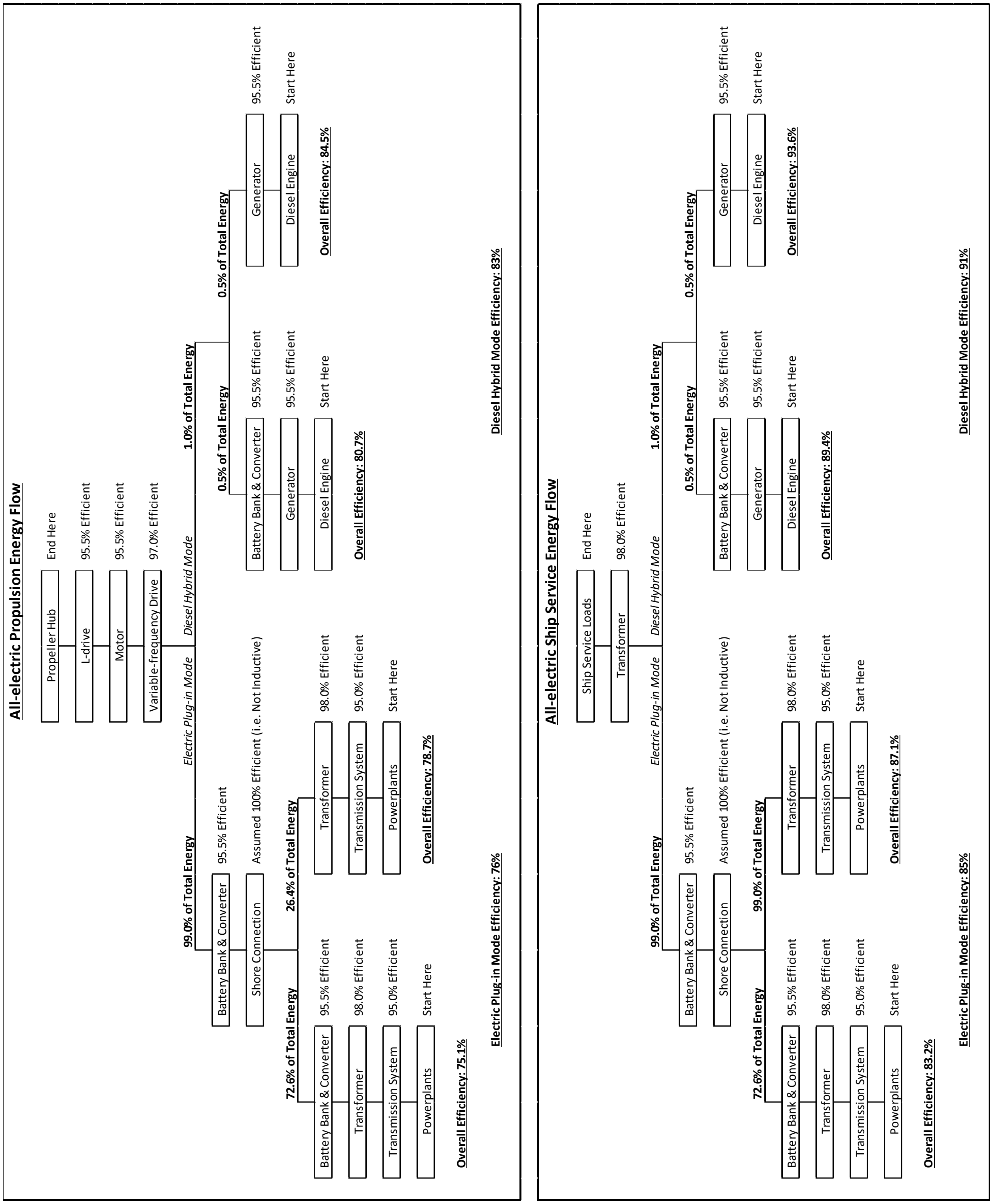


Exhibit 47 shows the arrangement of the all-electric system, with the trail of assumed equipment efficiencies and the calculated overall system efficiencies. This system operates in two different modes: it runs exclusively on electricity most of the time, and it uses supplemental energy from a diesel generator the rest of the time. A county official tells me that they expect 99% of the energy to come from the grid, so I have used that assumption in my calculations.[49] The overall propulsion system efficiency is estimated to be 76% back to the powerplant in plug-in mode and 83% back to the engines in diesel mode. The overall ship service system efficiency is estimated to be 85% back to the powerplant in plug-in mode and 91% back to the engines in diesel mode.

Exhibit 47. System efficiency diagrams for all-electric propulsion



Emissions Rate

In this appendix, I define the emissions rate as the amount of CO_2 released relative to the amount of useful energy released at the electric powerplant or diesel engine.

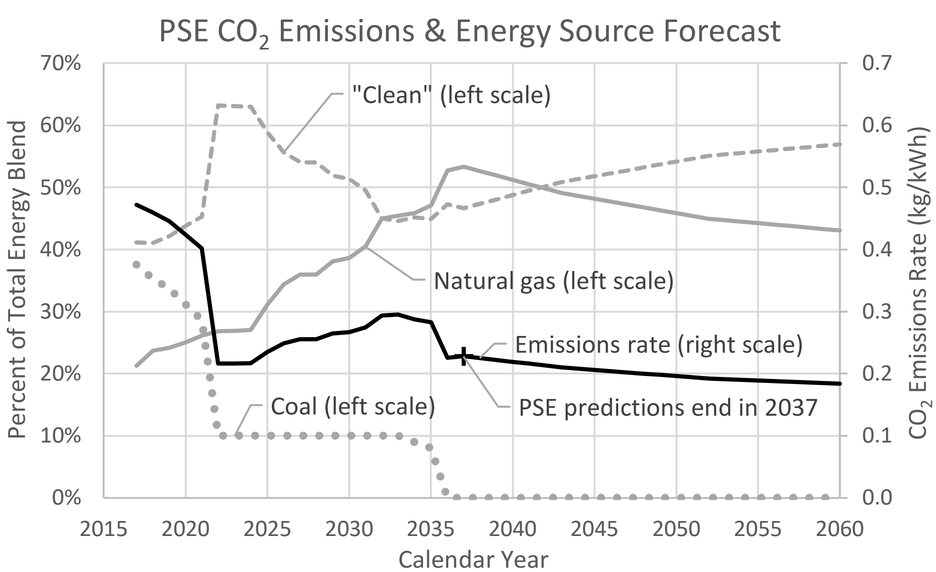
The chemical composition of each type of fuel determines the amount of CO_2 released during (complete) combustion. Therefore, fuel consumption and CO_2 emissions are directly proportional for a given type of fuel. Fuel consumption, on the other hand, is a function of the efficiency of the electric powerplant or diesel engine.

The EIA publishes all of the information necessary to calculate the efficiency and emissions rate for any powerplant in the nation. In 2017, the most recent year for data, the majority of Puget Sound Energy's (PSE's) electricity came from fossil fuels: 38% from coal (1.02 kg CO_2/kWh EIA national average), and 21% from natural gas (0.43 kg CO_2/kWh EIA national average).[183] According to PSE, their overall 2017 CO_2 emissions rate for electricity production was 0.49 kg CO_2/kWh.[184]

In order to comply with the Energy Independence Act[185] and the Clean Energy Transformation Act,[186] PSE has "committed to reducing its carbon footprint by 50 percent by 2040," including being 90% coal-free by 2025 and 100% coal-free by 2036.[115,187] I back-calculated PSE's emissions rate over time using the baseline emissions and demand cases presented in PSE's 2017 Integrated Resource Plan (IRP).[188] This plan only extends to 2037, so I extrapolated emissions to 2060, when the replacement ferry nominally retires.[116,189,190]

Exhibit 48 shows my forecast of PSE's future emissions rates and energy sources. There is a spike in "clean" energy that I attribute to power purchased from other system operators with lower carbon footprints in the years between PSE's coal phase-out and the completion of PSE's new natural gas plants.[115] PSE seems to leave off in 2037 with a heavy reliance on natural gas (53%), which I slowly tapered out toward cleaner sources in my extrapolation. A slow taper seemed reasonable based on what I know about PSE's upcoming investments in natural gas plants and the technical and economic challenges of converting the second half of the grid from stable, controllable sources (e.g. hydroelectric or natural gas) to intermittent, unpredictable sources (e.g. wind or solar).

Exhibit 48. Forecasted PSE emissions rate and energy source mix

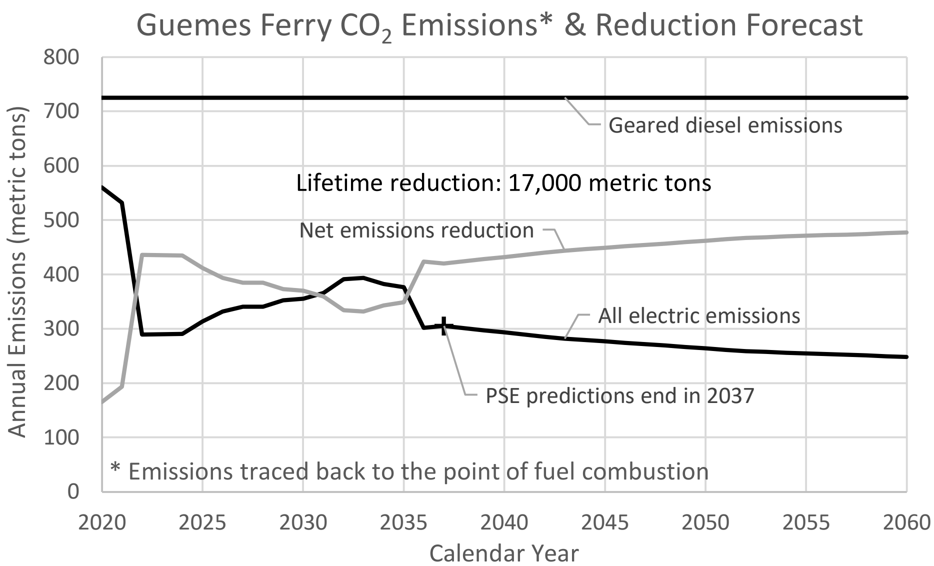


For the diesel engines, I combined the EIA's CO_2 chemistry balance (stoichiometry) for diesel combustion with fuel consumption data provided by a prominent diesel engine manufacturer.[191] I accounted for the engines' varying power levels, which affects their fuel efficiencies. I also added two hours of idling each day to each engine. From this information, I estimated an average CO_2 emissions rate of 0.66 kg CO_2/kWh throughout the life of the ferry.

Results

Exhibit 49 shows the result of my analysis at the point where fossil fuels are burned to power the ferry—i.e. at the powerplant or at the diesel engine. The two black lines show my forecasted emissions from the all-electric ferry and the geared diesel ferry. The gray line shows my forecasted reduction in emissions (i.e. the difference between the all-electric and the geared diesel). The all-electric ferry reduces emissions by 17,000 metric tons[105] over its 40-year life, or an average of 420 metric tons per year, at the point I have chosen to analyze. While this decrease is less than the county advertised, electrification still cuts the ferry's emissions by 57% when we consider the point where combustion occurs.

Exhibit 49. Forecasted annual CO_2 emissions and emissions reduction



There are many ways to frame a vehicle's environmental impact. This analysis has added a second frame to the county's first estimate, and a base of information on which to keep building more frames as we seek to reckon with the true cost of our comfortable lifestyles.

It is difficult to make identical comparisons. The all-electric ferry's efficiency includes the delivery of electricity from distant powerplants, whereas the geared diesel ferry's efficiency starts with the fuel sitting in the tanks. Neither efficiency accounts for the extraction, refining, and delivery of fuels to the points where they are burned. Nor do these efficiencies account for the environmental impact of making the hardware used to harvest or to consume the energy, be it solar panels or steam shovels, diesel engines or gas turbines.

There are also frames beyond fuels, dealing with the origins of everything from batteries and pistons to the structure of the ship itself. ANL's analysis method offers a comprehensive approach to answering these difficult questions. It has been applied successfully to cars,[192] but not yet to boats.

Beyond ANL's lifecycle analysis lies yet another frame: the opportunity cost of choosing one project over another. Assuming that there is a limited amount of money earmarked to combat global warming, we would want to spend that money on the projects that are most effective at reducing greenhouse gases.

Acknowledgments

I thank the mariners, mechanics, engineers, and administrators who make it possible to cross Guemes Channel every single day of the year, with impeccable safety and extremely high reliability, for a price we can generally afford when we really need to, while sharing a laugh and a smile.

I thank the members of Skagit County's government who have lent me a patient ear and an open mind. They have thoughtfully entertained my questions in good faith, recognizing that we all share a common goal. They understand that our democracy thrives on the respectful exchange of ideas, and that the process of good government consists of testing those ideas in the open.

I thank my colleagues in the engineering community for the fine and impartial work that they have done to help Skagit County better understand the breadth, costs, and consequences of available options, and for the documentation that they have provided to the county and the public. I thank them for being good-natured professionals as I built upon their work. I also thank the vendors, researchers, government officials, and other parties who support this document.

I thank past and present members of the Guemes Island Ferry Committee for upholding the duties set forth in their charter[193] and working to facilitate productive conversations between the community and the county.

I thank the people of Guemes Island for their propensity to help one another, to ask questions, and to value the free exchange of ideas.

I thank my friends who encouraged, influenced, and edited this document. It is much better for their recommendations. With that said, I take full responsibility for the contents and conclusions of this document.

Endnotes

[1] A county official told me: “I would very much like the community to engage in the design process; however, whenever we talk about the project in the public forums, I find that the focus tends to shift to the opposition of the project, and very little conversation happens about the new vessel.” Rachel Rowe (Skagit County). Email to Brent Morrison regarding cost, funding, range, and public commentary relating to replacement ferry: “RE: New Ferry Cost Documentation?” 2019-10-29.

[2] Skagit County. Resolution R20150428. 2015-12-29. Available [2019-10-10]: http://www.skagitcounty.net/Common/Documents/LFDocs/COMMISSIONERS000005/00/01/2a/00012ac9.pdf

[3] Per p. 2 of the Concept Design Report (endnote 6), the geared diesel propulsion system is considered the “baseline,” presumably because it represents the preponderance of the world’s existing propulsion installations, including the installation on the ferry we have today.

[4] Ken Fuller, P.E. (Executive Director, Washington State Board of Registration for Professional Engineers and Land Surveyors). Telephone call with Brent Morrison regarding whether this document should bear an engineering seal. 2019-11-20.

[5] Washington State Legislature. WAC 196-27A-020: Fundamental canons and guidelines for professional conduct and practice. 2002-12-13. Available [2019-11-11]: https://app.leg.wa.gov/WAC/default.aspx?cite=196-27A-020

[6] Glosten. Guemes Island Ferry Replacement: Concept Design Report. 2017-12-11. Available [2017-12-30]: https://www.skagitcounty.net/PublicWorksFerryReplacement/Documents/designreport/1b_Concept%20Design%20Report.pdf

[7] Jon Hodgdon said that he produced this graph and spreadsheet “acting as a ‘citizen volunteer (ex) naval architect,’ trying to assist Skagit County on this project wherever they tell me they’d like assistance.” The spreadsheet as-downloaded contained nonexistent grants and weighting factors that did not match Skagit County’s final weighting factors. I removed the nonexistent grants and updated the weighting factors to reflect Table 22 in the CDR. See: Jon Hodgdon. Excel spreadsheet entitled “Glosten Propulsion Scoring (Interactive) v20171209.xlsx.” 2017-12-09. Available by request from http://www.linetime.org.

[8] Dan Berentson et al. (Skagit County). “Project Memorandum: Guemes Island Ferry Replacement Project.” 2019-02-15. Available [2020-02-18]: https://www.skagitcounty.net/PublicWorksFerryReplacement/Documents/Project%20Memo%20to%20BCC%20RE_Vessel%20Size.pdf

[9] Washington State Legislature. RCW 39.26.160: Bid Awards—Considerations—Requirements and Criteria To Be Set Forth—Negotiations—Use of Enterprise Vendor Registration and Bid Notification System. Available [2020-02-11]: https://app.leg.wa.gov/rcw/default.aspx?cite=39.26.160

[10] An article in late 2017 or early 2018 in the Anacortes American reported that Skagit County had chosen to proceed with only the all-electric and plug-in hybrid ferry options.

[11] Rachel Rowe (Skagit County). Email to Brent Morrison regarding cost, funding, range, and public commentary relating to replacement ferry: “RE: New Ferry Cost Documentation?” 2019-10-29.

[12] I have heard operating-cost-based justifications for the electric ferry at Ferry Committee meetings over the past year. I also heard this justification from the ferry’s lead designer. Will Moon (Glosten). Telephone call with Brent Morrison regarding Appendix A. 2020-01-03.

[13] See Table 2 in the CDR.

[14] This finding is developed under Principle 3.

[15] Skagit County. Guemes Ferry Replacement Survey. 2017-09-12. Available [2019-10-02]: https://publicinput.com/1970

[16] See Table 23 in the CDR.

[17] Some of the problems and potential solutions are discussed in Linxi Kong et al. "Li-ion Battery Fire Hazards and Safety Strategies." Energies 11 (9). 2018. Available [20019-11-19]: https://www.mdpi.com/1996-1073/11/9/2191

[18] See Figures 23, 27, and 31 in the CDR.

[19] See 46 CFR §58.01-35: "Auxiliary machinery vital to the main propulsion system must be provided in duplicate unless the system served is provided in independent duplicate, or otherwise provides continued or restored propulsion capability in the event of a failure or malfunction of any single auxiliary component." US Government Publishing Office. "Subchapter F: Marine Engineering." CFR Title 46: Shipping. 1988-05-18. Available [2019-11-05]: https://www.ecfr.gov/cgi-bin/text-idx?gp=&SID=2f7a783c0bfbb82f924802c437390f40&mc=true&tpl=/ecfrbrowse/Title46/46CIsubchapF.tpl

[20] My perspective is based on many non-confidential conversations that I have had with several industry-wide colleagues, including battery vendors, over the past decade.

[21] Edith Walden. "Marine Industry Boosts Fleets of Battery-powered Vessels." Skagit County Ferry Replacement News. 2019-01. Available [2019-02-02]: https://www.skagitcounty.net/PublicWorksFerry/Documents/newsletter/newsletter0119.pdf

[22] According to Skagit County, "Since 2014, the Ferry Division has spent nearly half of its annual $2.5 million operating budget on maintenance of the vessel and associated machinery and repair projects. This has become increasingly burdensome on Skagit County's road fund with the annual subsidy from that fund contributing approximately $1 million per year in the last few years." Skagit County. "Guemes Island Ferry Replacement Project." N.d. Available [2020-02-06]: https://www.skagitcounty.net/departments/publicworksferryreplacement

[23] Fare revenues were determined from the following sources:

- Skagit County. 2019 Ferry Fare Revenue Target Report. 2019-04-23. Available [2020-01-07]: https://www.skagitcounty.net/PublicWorksFerry/Documents/SC%202019%20Revenue%20Target%20Report_Final.pdf
- Washington State Ferries. Route Statements for Fiscal Years 2013 to 2018. 2018-12-24. Available [2020-01-07]: https://www.wsdot.wa.gov/ferries/assets/FY2018RouteStatements.pdf
- The Red and White Fleet is privately held by the Crowley family (Thomas Crowley Escher et al.). The person I reached at the company preferred not to share revenue information. I estimate that revenue in 2018 was at least $10mn = (500,000 passengers x $20 per passenger) and perhaps as much as $22mn = (500,000 passengers x $44 per passenger), based on the following public information:
    - As of 2017, Red and White "carries approximately 500,000 passengers" per year. Elaine Forbes (Port of San Francisco). "Informational Presentation Regarding the Proposed Lease with Golden Gate Scenic Steamship Corporation." 2017-02-23. Available [2020-001-07]: https://sfport.com/sites/default/files/Commission/Documents/Item%2011A%20Golden%20Gate%20Scenic%20Lease%20Renewal.pdf
    - Tickets today range from $25 (youth Golden Gate Bay Cruise) to $80 (adult California Twilight Cruise). Red and White also charters its vessels for special events, which could reduce the average revenue per passenger. The average revenue per passenger is likely to be at least $20, because $20 is lower than the lowest ticket price. I have assumed that the average revenue per passenger is unlikely to be higher than the second-lowest adult ticket price, which is $44. Red and White Fleet. "Bay Cruises." Available [2020-01-07]: https://redandwhite.com/bay-cruises/

- On average for the year 2018, one Norwegian krone was worth about 8.3 U.S. dollars. Norled's operating revenue is available at: DSD Group. Annual Report and Accounts: 2018. 2019-04-11. Available [2020-01-07]: https://assets.website-files.com/59ae62f71c303d0001fea7ce/5d19f9042daf2f0804398c52_dsd_årsrapport2018_ENG-comp.pdf

[24] Fleet sizes were determined from the following sources:

- Skagit County. "Guemes Island Ferry." N.d. Available [2020-02-20]: https://www.skagitcounty.net/Departments/PublicWorksFerry/about.htm
- Washington State Ferries. "Ferries: Vessels." N.d. Available [2020-02-20]: https://www.wsdot.wa.gov/ferries/vesselwatch/Vessels.aspx
- Red and White Fleet. "Meet the Fleet." N.d. Available [2020-02-20]: https://redandwhite.com/meet-the-fleet/
- Norled. "About Norled." N.d. Available [2020-02-20]: https://www.norled.no/en/about-norled/

[25] The numbers of electric and hybrid vessels were determined from the following sources:

- Skagit County. "Guemes Island Ferry Replacement Project." Available [2020-02-20]: https://www.skagitcounty.net/departments/publicworksferryreplacement
- Elliott Bay Design Group. Jumbo Mark II Class Hybrid Integration Study. Rev. A, 2020-01-17. Available [2020-02-20]: https://www.wsdot.wa.gov/ferries/assets/WSF-HybridSystemIntegration-Study.pdf
- Red and White Fleet. "Meet the Fleet." N.d. Available [2020-02-20]: https://redandwhite.com/meet-the-fleet/
- Sean Puchalski. "All-electric Car Ferry." Electric & Hybrid Marine Technology International. 2015-04. Available [2019-12-09]: http://viewer.zmags.com/publication/3e159aac#/3e159aac/86

[26] I used the route planner in Google Maps to calculate distance by road. Available [2019-03-16]: https://www.google.com/maps

[27] I used Google Maps (endnote 26) to search for hospitals.

[28] Calculations contrasting the electric ferry with local households are as follows:

Variable	Quantity	Unit	Page	Source
Avg. home usage	17.5	kWh/day	n/a	My PSE tools, which provides average usage of downtown Anacortes homes
Avg. home draw	0.73	kW	n/a	Usage / 24 hours
Factor for daytime	1.04	–	n/a	EIA Realtime Grid for Seattle City Light, minimum of winter & summer during weekday ferry operating hours: https://www.eia.gov/realtime_grid/#/status?end=20200220T10
Daytime home draw	0.76	kW	n/a	Avg. home draw x factor for daytime
Ferry energy cons.	133	kWh/RT	n/a	Ferry CO2 emissions calculations, with effy. to shore conn. (Appendix D)
Ferry charge time	8.0	min	n/a	Inferred from CDR Table 13 and Figure 29
Dock draw	1,001	kW	n/a	Energy consumption / charge time (x 60 min/hr). Rated for 1,200 kW.
Shoreside effy.	0.93		n/a	Ferry CO2 emissions calculations (Appendix D)
Grid draw	286	kW	n/a	Energy cons. x 2 / shore effy. (half-hour round-trips). Rated for 310 kW.
Dock demand	**1,315**	**homes**	**n/a**	**Dock draw / daytime home draw**
Min. grid demand	**376**	**homes**	**n/a**	**Grid draw / daytime home draw**

[29] See sections 3.5.5.4 and 3.6.1.2 of the CDR. See also Sean Puchalski's article (endnote 32).

[30] CDR Figure 29 shows that charging occurs from the instant the ferry arrives until the instant the ferry departs, but obviously there must be some allowances for the time required to connect and disconnect the charging equipment. I suspect that the ferry must be made fast to the dock whenever the charging equipment is connected, creating a longer arrival/departure sequence.

[31] See Section 3.5.5 in the CDR.

[32] Sean Puchalski. "All-electric Car Ferry." Electric & Hybrid Marine Technology International. Available [2019-12-09]: http://viewer.zmags.com/publication/3e159aac#/3e159aac/86

[33] See Section 3.5.5.3 in the CDR.

[34] See NMC cycles for 20% and 30% depth of discharge on Figure 22 in the CDR. The planned depth of discharge is 20% per Section 3.5.2 of the CDR.

[35] Although the magnitudes of the data are known to be incorrect, the spread of energy consumption follows a plausible trend, revealing a right-skewed probability distribution. See Art Anderson Associates. Guemes Island Ferry Propulsion and Power Study. 2016-06-27. Available [2016-07-28]: https://www.skagitcounty.net/PublicWorksFerry/Documents/Replacement/Guemes%20Island%20Ferry%20Propulsion%20%20Power%20Study.pdf

[36] There are also limitations to how quickly the shore and vessel batteries can charge and discharge, but we do not seem to be up against those limitations. See section 3.5.2 in the CDR.

[37] See Section 3.6.1.3 in the CDR. The 95% operability estimate is linked to wind conditions.

[38] The projected cost of the 28-car ferry indicates that Skagit County chose the "28-car Limited" option in: Glosten. Project Memorandum: 28-car Options Cost Estimate. 2018-03-30. Available [2019-10-28]: https://www.skagitcounty.net/PublicWorksFerryReplacement/Documents/17097-043-02%20GIFR%2028-Car%20Cost%20Project%20Memorandum.pdf

[39] See pages 2 and 3 of the 28-car Options Cost Estimate (endnote 38).

[40] Calculations for battery vs. diesel weight are as follows:

Variable	Quantity	Unit		Source
Diesel LHV	42,780	kJ/kg	n/a	Caterpillar. *Comparing Volumetric Fuel Consumptions.* 2019-06: https://www.cat.com/en_US/by-industry/electric-power-generation/Articles/White-papers/comparing-volumetric-fuel-consumptions.html
Diesel Density	**11.9**	**kWh/kg**	**80**	**Lindeburg. Engineering Unit Conversions. 2009.**
Battery Capacity	1,050	kWh	A-10	Glosten. Guemes Ferry Concept Design Report. 2017-12-11: https://www.skagitcounty.net/PublicWorksFerryReplacement/Documents/designreport/1b_Concept%20Design%20Report.pdf
Battery Weight	19,535	lb	A-10	Glosten. Guemes Ferry Concept Design Report. 2017-12-11: https://www.skagitcounty.net/PublicWorksFerryReplacement/Documents/designreport/1b_Concept%20Design%20Report.pdf
Battery Mass	8,861	kg	110	Lindeburg. Engineering Unit Conversions. 2009.
Battery Density	**0.118**	**kWh/kg**	**n/a**	**Battery Mass / Battery Capacity**
Diesel/Battery Ratio	**100**	**–**	**n/a**	**Diesel Density / Battery Density**

[41] Calculations for battery vs. diesel tank cost are as follows:

Variable	Quantity	Unit	Page	Source
Tank length	4.0	ft	3	Glosten. Concept General Arrangement. 2017-12-11.
Tank breadth	8.0	ft	3	Ibid.
Tank height	13.0	ft	22	Glosten. Concept Design Report. 2017-12-11. Table 7 says 6k gal total, so 3k gal per tank. That requires 13' height as drawn, which extends the full depth of the vessel. Such a deep tank imparts a lot of head pressure.
Tank volume	416	ft^3	n/a	Volume = length x breadth x height
Tank permeability	97.5%	–	n/a	Standard assumption 97.5-98.5.
Tank capacity	3,034	gal	26	Lindeburg. Engineering Unit Conversions. 2009.
Tank capacity'	11.49	m^3	30	Ibid.
Diesel LHV	42,780	kJ/kg	n/a	Caterpillar. *Comparing Volumetric Fuel Consumptions.* 2019-06: https://www.cat.com/en_US/by-industry/electric-power-generation/Articles/White-papers/comparing-volumetric-fuel-consumptions.html
Diesel mass density	838.9	kg/m^3	n/a	Ibid.
Diesel energy density	3.59E+07	kJ/m^3	n/a	Energy density = LHV x mass density
Tank energy	**4.12E+08**	**kJ**	**n/a**	**Tank energy = capacity' x energy density**

Continued on the following page…

Calculations for battery vs. diesel tank cost (continued):

Variable	Quantity	Unit	Page	Source
Tank surface area	376	ft^2	n/a	Area = 2 x (length x breadth + breadth x height + length x height). Ignoring commonality with WT bhd and other tank, which would reduce matl.
Tank smear factor	50%	–	n/a	Generally the upper end of structure smear.
Tank drop factor	20%	–	1	Glosten. Engineer's Cost Estimate. 2017.
Tank baffle factor	25%	–	n/a	Additional plating for baffles. Small tank does not need many baffles.
Tank plate area	733	ft^2	n/a	Total area = area x (1 + smear factor + drop factor + baffle factor)
Plate unit weight	10.2	lb/ft	n/a	Glosten. Structural Midship Section. 2017-12-11. 1/4" plate shown at midship bhd. Assume sufficient for tank loads on same bhd per GA. https://www.portlandbolt.com/technical/tools/plate-weight-calculator/
Tank weight	3.34	LT	n/a	Weight = plate area x plate weight / 2240 lb/LT
Labor rate	4,900	$/LT	1	Glosten. Engineer's Cost Estimate. 2017.
Material rate	7.4	$/sf	n/a	https://www.metalsdepot.com/steel-products/steel-plate (10'x4' plate)
Additional markup	46%	–	1	Glosten. Engineer's Cost Estimate. 2017.
Allowance for maint.	50%	–	n/a	Lifetime maintenance costs brought back to today. Fuel tanks are low-maint.
Tank cost	**42,518**	**USD**	**n/a**	**Cost = (area x matl rate + weight x labor rate) x (1 + markup + maintenance)**
Tank storage cost	**9,695**	**kJ/USD**	**n/a**	**Tank storage cost = tank energy / tank cost**
Battery size	1,050	kWh	A-9	Glosten. Guemes Ferry Concept Design Report. 2017-12-11.
Battery size'	3,780,000	kJ	80	Lindeburg. Engineering Unit Conversions. 2009.
Battery cost	1,964,504	$	A-9, A-12	Initial battery plus four replacements, discounted at 5% p.a. Glosten. Guemes Ferry Concept Design Report. 2017-12-11.
Battery storage cost	**1.92**	**kJ/USD**	**n/a**	**Battery storage cost = battery size' / battery cost**
Tank-battery ratio	**5,039**	**–**	**n/a**	**Tank battery ratio = tank storage cost / battery storage cost**

This comparison of cost does not account for the labor to integrate these energy storage devices with the vessel's structure or systems. It is meant to illustrate the orders of magnitude that separate the capital costs of these storage technologies, in the same way that the costs of diesel fuel and electricity can be contrasted when considering operating costs.

42 Section 4.8 in the CDR indicates that the new ferry is expected to carry a two-week fuel supply. Table 9 in the CDR indicates that 10% diesel reserve is assumed, which is standard practice.

43 This calculation is based on an average of 8,718 round trips per year, assuming 165 peak round trips for 19.1 weeks and 159 off-peak round trips for 32.9 weeks, plus a 4% allowance for double runs, per the 2018-2019 schedule. The latest peak and off-peak schedules are available at the following web addresses:

- https://www.skagitcounty.net/PublicWorksFerry/Documents/Brochure_PeakFares.pdf
- https://www.skagitcounty.net/PublicWorksFerry/Documents/Brochure_NONPeakFares.pdf

44 Maitane Berecibar et al. "Degradation Mechanism Detection for NMC Batteries based on Incremental Capacity Curves." World Electric Vehicle Journal 8 (2). 2016-06-24. Available [2019-11-05]: https://www.mdpi.com/2032-6653/8/2/350

45 For Exhibit 8 I have assumed a battery life of 8 years (CDR Section 3.6.4) with 3% annual capacity degradation (Berecibar et al. Figure 1): 5.0 round trips • 1.03^{-8} = 3.9 round trips.

46 This approach is a bit simplistic, because during operations it is neither possible nor advisable to discharge a fuel tank to zero gallons or a battery to zero volts. This means that the all-electric ferry could not complete five round trips on one full charge, nor could the geared diesel ferry complete 34 round trips on an empty tank. Glosten designed the electric ferry "to complete two round trips without charging" in "emergency response scenarios" (CDR Section 4.8).

47 In Glosten's words, an all-electric ferry is "significantly reliant on shore infrastructure for operations." See Section 3.5.4.3 in the CDR.

48 This is my general understanding of how a backup generator would serve an all-electric Guemes ferry. Section 3.5.4.4 of the CDR provides some corroborating information.

49 I suspect that experience will prove 1% to be an unrealistically low number for backup generator reliance, but I am using it since it is the formal estimate from Skagit County, per endnote 11.

[50] Brent Morrison. Email to Rachel Rowe (Skagit County) requesting clarification on the power rating of the replacement ferry's propulsion units relative to the power rating of the backup generator: "RE: New Ferry Cost Documentation?" 2019-12-06.

[51] The hull shape and mass properties of double-ended, open-top, monohull ferries make them susceptible to snappy rolling and side-guard slamming. I have witnessed this effect firsthand on the existing Guemes ferry. The new ferry's greater freeboard (Sections 2.6 and 4.2 of the CDR) could increase the wave height at which motions become uncomfortable, thereby improving operability. The new ferry's much finer bow could increase the tolerable range of headings to waves, which could help make the route length less extreme when avoiding beam waves.

[52] My father took the picture in Exhibit 9 on 2017-05-23. I estimate the ferry would have laid down a trackline of roughly 1.4 nautical miles to get to this location, whereas a one-way crossing when beset by current is commonly 0.6 nautical miles.

[53] I posed the question of operability to an Airlift Northwest pilot but have not heard back. Instead I am relying on Chart 6-2 of: National Interagency Fire Center. <u>Interagency Helicopter Operations Guide</u>. 2009-06. Available [2019-10-04]: https://www.nifc.gov/PUBLICATIONS/ihog/chapters/2009chapter06.pdf)

[54] Cancellations were determined from emails sent by Guemes_Island_Ferry@skagitcounty.net on the following dates: 2016-12-20, 2017-02-10, 2017-03-09, 2017-03-29, 2017-05-23, 2018-02-17, 2018-12-14, 2019-02-04, and 2019-04-26. Some weather cancellations occurred during maintenance periods when the route was served by Arrow Launch Service, which provided useful insight into the weather operability limits of Arrow's vessels. I used these cancellations to select an associated limiting windspeed and wind direction from the wind dataset at Smith Island. National Data Buoy Center. "NDBC Station SISW1 Historical Data." 1984 to 2019. Available [2019-02-02]: https://www.ndbc.noaa.gov/station_history.php?station=sisw1

[55] Many of these scenarios are taken from Section 5.2.1 of the Transportation System Assessment, but I removed the duration and weather limitations. Glosten. <u>Guemes Island Ferry Replacement: Transportation System Assessment</u>. Rev. –, 2017-12-14. Available [2020-01-04]: https://www.skagitcounty.net/PublicWorksFerryReplacement/Documents/designreport/2b_Transportation%20System%20Assessment.pdf

[56] See Section 3.6.1.4 in the CDR.

[57] See Section 5 in the Transportation System Assessment (endnote 55).

[58] Battery research is flourishing right now, but this era of experimentation precedes an era of stability. Technological visionary Bill Gates recently quipped about "all the battery companies I've lost money on" by way of his Breakthrough Energy Fund. He makes this comment at 5:38 in: Bloomberg Markets and Finance. "Bill Gates on AI, Climate, Carbon Tax, Nuclear Power, China." 2019-11-21. Available [2019-12-29]: https://www.youtube.com/watch?v=vapTJLUSvpQ

[59] Details are as follows:

- *Ampere* won the award in early September 2014 according to: Mike Schuler. "All-electric Ferry Named Ship of the Year at SMM." <u>gCaptain</u>. 2014-09-10. Available [2019-10-02]: https://gcaptain.com/zerocat-120-battery-powered-ferry-named-ship-of-the-year/
- The award was presented at the vessel's christening in October 2014. "Ship of the Year 2014 døpt i Hardanger." <u>Skipsrevyken</u> 2014 (6). 2014-12. Available [2019-10-02]: https://issuu.com/skipsrevyen/docs/skipsrevyen_nr_6_2014
- Skipsrevyken's writeup can be found here: "Ship of the Year 2014." <u>Skipsrevyken</u>. 2015-01-18. Available [2019-10-02]: https://issuu.com/skipsrevyen/docs/soty2014
- Ampere's maiden voyage took place in May 2015 according to: Odd Moen. "The e-ferry (r)evolution." <u>Siemens Ingenuity</u>. 2018-08-29. Available [2019-10-02]: https://ingenuity.siemens.com/2018/08/the-e-ferry-revolution/

[60] Washington State Governor's Office. "Leading in the maritime sector: Washington launches Maritime Blue 2050 initiative." 2017-12-12. Available [2019-11-09]: https://medium.com/wagovernor/leading-in-the-maritime-sector-washington-launches-maritime-blue-2050-initiative-d54f7d5730cc

See also: Washington State Department of Commerce. "Charting Washington State's Course To Be Nation's Most Sustainable Maritime Industry by 2050." 2017-12-17. Available [2019-11-09]: https://www.commerce.wa.gov/news-releases/charting-washington-states-course-nations-sustainable-maritime-industry-2050/

[61] United States Coast Guard. N.d. Investigation Activity Report: *Campbell Foss* Fire. Available [2019-10-12]: https://cgmix.uscg.mil/IIR/IIRSearch.aspx (Search for MISLE activity number 4417794.)

[62] Foss Maritime. *Campbell Foss* Hybrid Retrofit Final Report. N.d. Available [2019-11-11]: https://ww3.arb.ca.gov/msprog/aqip/demo/demo%20final%20reports/campbell_foss_hybrid_final_report_052913.pdf

[63] Mikael Holter et al. "The Next Ferry You Board Might Run on Batteries." Bloomberg Hyperdrive. 2018-03-12. Available [2019-10-04]: https://www.bloomberg.com/news/features/2018-03-13/the-next-ship-you-board-might-run-on-batteries

[64] HMS Consulting. Vessel Propulsion System Conversion and Vessel Maintenance RFP: Alabama Department of Transportation, Gees Bend Ferry Propulsion Conversion [as amended]. 2018-02-12. Available [2019-09-11]: http://hmsgmconsulting.com/wp-content/uploads/2018/02/Gees-Bend-Conversion-Shipyard-RFP-012418-DJF-2.pdf

[65] News 5 WKRG. "Alabama ferry makes history as first all-electric vehicle ferry in America." 2019-04-10. Available [2019-09-11]: https://www.wkrg.com/mobile-county/alabama-ferry-makes-history-as-first-all-electric-vehicle-ferry-in-america/

[66] Norwegian Maritime Authority. Battery Fire with Subsequent Gas Explosion. 2019-10-14. Available [2019-10-15]: https://www.sdir.no/en/shipping/legislation/directives/battery-fire-with-subsequent-gas-explosion/

[67] "Ferry Explosion Brings New Focus on Battery Safety." Cruise Industry News. 2019-10-17. Available [2019-10-17]: https://www.cruiseindustrynews.com/cruise-news/21743-ferry-explosion-brings-new-focus-on-battery-safety.html

[68] "Marine Accident Roundup: 16th October 2019." Insurance Marine News. 2019-10-16. Available [2019-11-11]: https://insurancemarinenews.com/insurance-marine-news/marine-accident-round-up-16th-october-2019/

[69] Minimizing ownership cost is stated as the reason for replacing the existing ferry on Skagit County's ferry replacement website: Skagit County. "Guemes Island Ferry Replacement Project." N.d. Available [2019-10-02]: https://www.skagitcounty.net/departments/publicworksferryreplacement

The sentence seems to have been taken verbatim from page 2 of: Elliott Bay Design Group. M/V *Guemes*, O.N. 601686: Ferry Replacement Plan. Rev. B, 2013-11-22. Available [2014-02-12]: https://www.skagitcounty.net/PublicWorksFerry/Documents/Replacement/MV%20GUEMES%20Ferry%20Replacement%20Plan_22Nov2013.pdf

[70] These three presentations suggested payback periods of three, five, and eight years, respectively:

- Joseph Payne (EESI Marine). "EZE Ferry." Presentation to the Guemes Island Ferry Committee. 2015-10-25. Available [2019-10-10]: http://www.linetime.info/EZEferry%20GIFC%20201501025.pdf
- Joseph Payne (EESI Marine). "EZE Ferry." Presentation to the Skagit County Board of Commissioners. 2015-12-08. Available [2019-10-10]: https://skagit.granicus.com/MediaPlayer.php?view_id=2&clip_id=2099

- Luke Briant (Siemens). "Marine Design and Technology Perspective." Presentation to the Skagit County Board of Commissioners. 2016-06-14. Available [2019-10-10]: https://skagit.granicus.com/MediaPlayer.php?view_id=8&clip_id=2233

[71] Skagit County. Skagit County Ferry Replacement News. 2019-05. Available [2019-10-02]: https://www.skagitcounty.net/PublicWorksFerryReplacement/Documents/newsletter/newsletter052319.pdf

Per this newsletter, one grant provides up to $1.5mn for shoreside infrastructure, and another grant provides up to $1.2mn for design. I applied the full shoreside infrastructure grant to the all-electric and plug-in hybrid options, because shoreside infrastructure costs were always much higher than the total value of the grant. I applied the $1.2mn design grant to each option at a rate of 5% of the construction cost, per Glosten's Engineer's Cost Estimate, up to the limit of $1.2mn (which was never reached).

[72] County Road Administration Board. County Ferry Capital Improvement Program (CFCIP) — WAC 136-400 Project Application Guidance. 2017-01. Available [2019-10-24]: http://www.crab.wa.gov/programs/ferry/dcs/170124CFCIPWACsummary.pdf

[73] Elliott Bay Design Group. M/V Guemes, O.N. 601686: Ferry Replacement Plan. Rev. B, 2013-11-22. Available [2014-02-12]: https://www.skagitcounty.net/PublicWorksFerry/Documents/Replacement/MV%20GUEMES%20Ferry%20Replacement%20Plan_22Nov2013.pdf

[74] Relative to Exhibit 42 in Appendix B, I adjusted the costs in this graph from November 2013 dollars to November 2017 dollars, to match the more recent cost estimates by Glosten, using: U.S. Bureau of Labor Statistics. "Producer Price Index series PCU3366113366119 ("ship building and repairing-Nonmilitary self-propelled ships, new construction, not seasonally adjusted")." Available [2020-02-22]: https://data.bls.gov/cgi-bin/dsrv?pc

[75] The consensus seems to be that the existing Guemes ferry could operate for another decade without capacity issues, based on the resources below (disclaimer: I wrote the first resource, and I would write it slightly differently today). The downsizing of the replacement ferry's capacity to 28 cars reinforces Skagit County's commitment to gradual increases in vehicle demand over time. Skagit County has some control over vehicle demand by changing fares, parking, schedules, and other incentives.

- See Figure 4 in: Glosten. Guemes Island Ferry Replacement: Vessel Capacity Study. 2017-10-20. Available [2020-02-22]: https://www.skagitcounty.net/PublicWorksFerryReplacement/Documents/designreport/2a_Vessel%20Capacity%20Study.pdf
- See Exhibit 21 in: Berk Consulting. Guemes Ferry Replacement Environmental Assessment. 2018-04-13. Available [2020-02-22]: https://www.skagitcounty.net/PlanningAndPermit/Documents/FerryEnviro/Environmental%20Assessment_2018_0412_wAppx_sig.pdf

[76] According to the CRAB grant programs manager, "since there is no sunset, the county could conceivably be paid the full $7,500,000 (20 years) without actually building a boat within that time frame. The funds are conditioned, however, on building a boat." Randy Hart, P.E. (County Road Administration Board). Email to Glen Veal regarding the details of CRAB grant disbursement: "RE: CRAB Grant Skagit County." 2020-01-21.

[77] The surcharge was expected to raise $245k in 2019. Skagit County. "Notice of Public Comment Opportunity: Ferry Vessel Replacement Surcharge." 2018-03-26. Available [2020-02-16]: https://www.skagitcounty.net/PublicWorksFerry/Documents/Surcharge%20Public%20Hearing%20Handout%20041718.pdf

[78] Per Figures 11 and 12 in the Replacement Plan.

[79] National Institute of Standards and Technology (NIST), U.S. Department of Commerce. NIST Handbook 135: Life-cycle Costing Manual for the Federal Energy Management Program. 1996-

02-01. Available [2019-01-19]: https://www.nist.gov/publications/life-cycle-costing-manual-federal-energy-management-program-nist-handbook-135-1995

[80] Kurt Jankowski, P.E. (Elliott Bay Design Group). Telephone call with Brent Morrison regarding Appendix B and methods used in the Guemes Ferry Replacement Plan. 2019-11-20.

[81] Sections 3.6 and 3.6.4 in the CDR suggest that future dollars should be devalued by 3% to 5% per year, with the latter rate used for cutting-edge technology such as batteries.

[82] Skagit County's CRAB grant pays $7.5mn over 15-20 years, in amounts no greater than $500k per year (endnote 76). The minimum annual revenue under this structure would be $7.5mn / 20 years = $375k per year. The surcharge is estimated to raise $245k per year in 2019 dollars (endnote 77). The combined nominal annual revenue from the CRAB grant and the surcharge is $375k + $245k = $620k.

[83] See Appendix A in the Ferry Replacement Plan.

[84] See Figure 5 in the Concept Design Report.

[85] Delphi Maritime. M/V *Guemes* Condition & Valuation Report. 2019-07-31. Available [2019-12-14]: https://www.skagitcounty.net/PublicWorksFerry/Documents/2019-0753%20MV%20Guemes%20C%20%20V%20Final.pdf

[86] I believe that the years elapsed between the reports may not be the cause of this discrepancy, because both reports assume that major machinery would be replaced with new equipment, and the Delphi marine survey (which Exhibit 14 shows is more pessimistic on post-refit longevity than the Ferry Replacement Plan is) found that the hull would last another 20 years.

[87] The executive summary of the Ferry Replacement Plan suggests that the existing ferry should be overhauled or replaced before 2024. I have detected a greater sense of urgency related to capital ferry improvements from Skagit County officials and some Guemes Island Ferry Committee members at public meetings since the Replacement Plan was released. Skagit County's replacement webpage (endnote 22) calls attention to the financial aspects that may be driving this urgency: "In the last few years, haul-out and dry dock costs have increased substantially. Since 2014, the Ferry Division has spent nearly half of its annual $2.5 million operating budget on maintenance of the vessel and associated machinery and repair projects. This has become increasingly burdensome on Skagit County's road fund with the annual subsidy from that fund contributing approximately $1 million per year in the last few years."

[88] According to Resolution R20150428 (endnote 2), "Skagit County does not currently have funds that are allocated for vessel replacement."

[89] Per endnote 71, I applied the $1.5mn shoreside grant completely to the all-electric and plug-in hybrid vessels. I applied the $1.2mn design grant at a rate of 5% of construction cost, up to the limit of $1.2mn (which was never reached). I applied the full CRAB grant to all vessels, as their capital costs after other grants remained greater than $7.5mn. I explain my rationale for applying the CRAB grant to all vessels on page 6 of this document.

[90] County Road Administration Board. 2017-01. County Ferry Capital Improvement Program (CFCIP) — WAC 136-400 Project Application Guidance. Available [2019-10-24]: http://www.crab.wa.gov/programs/ferry/dcs/170124CFCIPWACsummary.pdf

[91] Shipbuilding prices have only increased 1.8% since November 2017, per the Producer Price Index for shipbuilding (endnote 74).

[92] According to people who attended the forum at the Guemes Island Community Center on 2019-11-07, Will Moon of Glosten said that the existing ferry would be kept on standby for one year after the new electric ferry enters service.

[93] See Section 1.2 in the Transportation System Assessment.

[94] Glosten assumes a residual value of $0 for all propulsion assets at the end of the 40-year evaluation period. I have carried that assumption.

[95] I assume towing must be more expensive than running the ferry with a crew, because I understand that Skagit County presently does not tow the ferry when visiting shipyards as far away as Seattle.

[96] See Section 3.5.2 in the CDR.

[97] Per p. A-9 of the CDR, batteries cost $650/kWh today. Per table 2 of the 28-car Options Cost Estimate, the "28-car limited" option has a total battery capacity (vessel plus shore) of 1,500 kWh. Thus the total battery cost today would be $650 • 1,500 = $975,000.

[98] See Table 8 of: Elliott Bay Design Group. Jumbo Mark II Class Hybrid Integration Study. Rev. A, 2020-01-17. Available [2020-02-20]: https://www.wsdot.wa.gov/ferries/assets/WSF-HybridSystemIntegration-Study.pdf

[99] Guemes Island Ferry Committee. "Ferry Committee BUILD Grant Support." 2018-10-25. Available [2019-03-31]: http://gifc.octopia.com/pages/45379/Ferry-Committee-BUILD-Grant-Support/

[100] Briana Alzola. "State Grants County Funding for Electric Ferry Terminal Upgrades." Anacortes American. 2019-05-29. Available [2020-02-23]: https://www.goskagit.com/anacortes/news/state-grants-county-funding-for-electric-ferry-terminal-upgrades/article_1fe715de-81a2-11e9-b83f-436779a68399.html

[101] See Table 23 and sections 3.7.5 and 3.7.6 in the CDR.

[102] Intergovernmental Panel on Climate Change. Special Report: Global Warming of 1.5°C: Summary for Policymakers. 2019. Available [2019-12-03]: https://www.ipcc.ch/sr15/chapter/spm/

[103] Per-Anders Enkvist et al. (McKinsey). A Cost Curve for Greenhouse Gas Reduction. 2007. Available [2019-10-09]: https://www.mckinsey.com/business-functions/sustainability/our-insights/a-cost-curve-for-greenhouse-gas-reduction

[104] McKinsey and many other organizations focused on greenhouse-gas reduction use CO_2 equivalent (CO_2e) as a measurement unit for a range of greenhouse gases. One ton of CO_2e is the quantity of any greenhouse gas that has the equivalent warming effect of one ton of CO_2. Different gases persist in our atmosphere for different periods of time; CO_2e is usually calculated with a timeframe of one century. See: Zeke Hausfather. "Understanding Carbon Dioxide Equivalence." Yale Climate Connections. Available [2020-02-20]: https://www.yaleclimateconnections.org/2009/01/common-climate-misconceptions-co-equivalence/

[105] A metric ton is 1,000 kg, or 2,200 lb.

[106] Per the large graph on page 13 of the IPCC summary (endnote 102), to reach the IPCC's 1.5°C goal with confidence, humanity's CO_2 output would need to drop from roughly 40 Gt in 2020 to roughly 20 Gt in 2030, a drop of roughly 20 Gt (i.e. 50%) over a decade.

[107] In early 2007, when McKinsey staff issued their report (endnote 104), €30 was equivalent to $39. I adjusted this figure from 2030 dollars to 2020 dollars assuming a 1.5% inflation rate, which is somewhat low by historical standards, to err toward a higher cost today: $\$39 \bullet 1.015^{-10} = \$34$.

[108] The World Bank. "What Is Carbon Pricing?" N.d. Available [2019-10-19]: https://carbonpricingdashboard.worldbank.org/what-carbon-pricing

[109] Organization for Economic Cooperation and Development and World Bank Group. The FASTER Principles for Successful Carbon Pricing. 2015-09. Available [2019-10-19]: https://www.oecd.org/environment/tools-evaluation/FASTER-carbon-pricing.pdf

[110] The social cost of one ton of CO_2 in Washington State in 2020 is $74 in 2018 dollars. Using the Consumer Price Index to adjust that value from January 2018 to January 2020, the social cost becomes $74 • 258.820 ÷ 248.816 = $77. See the following sources:

- Washington Utilities and Transportation Commission. "Social Cost of Carbon." N.d. Available [2019-11-12]: https://www.utc.wa.gov/regulatedIndustries/utilities/Pages/SocialCostofCarbon.aspx
- U.S. Bureau of Labor Statistics. "Consumer Price Index series CUSR0000SA0 ("all items in U.S. city average, all urban consumers, seasonally adjusted.")." Available [2020-02-20]: https://data.bls.gov/cgi-bin/dsrv

[111] The social cost of one ton of CO_2 at the federal level in 2020 is $42 in 2007 dollars. Using the Consumer Price Index (endnote 110) to adjust that value from January 2007 to January 2020, the social cost becomes $42 • 258.820 ÷ 203.437 = $53. See: U.S. Environmental Protection Agency. "Social Cost of Carbon." 2016-12. Available [2019-11-12]: https://19january2017snapshot.epa.gov/sites/production/files/2016-12/documents/social_cost_of_carbon_fact_sheet.pdf

[112] Skagit County Public Works. Annual Report: 2018. 2019-04. Available [2019-11-11]: https://www.skagitcounty.net/PublicWorks/Documents/2018%20Public%20Works%20Annual%20Report.pdf

[113] Although I have not been able to find Skagit County's documentation of 619,359 kg CO_2 emissions savings, I get a number within about 1% of its estimate by the following calculation:

Variable	Quantity	Unit	Page	Source
Fuel Consumption	7.176	gal/RT	4	Art Anderson Associates. Guemes Ferry Propulsion & Power Study. 2016-06-17: https://www.skagitcounty.net/PublicWorksFerry/Documents/Replacement/Guemes%20Island%20Ferry%20Propulsion%20%20Power%20Study.pdf
CO2 from Diesel	10.16	kg/gal	n/a	https://www.eia.gov/environment/emissions/co2_vol_mass.php
CO2 Output per RT	72.91	kg/RT	n/a	Fuel Consumption x CO2 Output from Diesel
Scheduled Annual Round Trips (Without Doubles)	8,383	RT/yr	n/a	https://www.skagitcounty.net/PublicWorksFerry/Documents/ ...Brochure_PeakFares.pdf (for peak schedule) ...Brochure_NONPeakFares.pdf (for nonpeak schedule)
Annual CO2 Output	**611,189**	**kg/yr**	**n/a**	**CO2 Output per RT x Annual Round Trips**

[114] Effective exhaust stack design and placement can greatly reduce the concentration of exhaust fumes on deck. It is possible (and common today) to optimize stack placement based on a study of exhaust plume flow using computational fluid dynamics (CFD).

[115] Puget Sound Energy. Integrated Resource Plan. 2017. Available [2019-10-02]: https://www.pse.com/-/media/PDFs/001-Energy-Supply/001-Resource-Planning/8a_2017_PSE_IRP_Chapter_book_compressed_110717.pdf

[116] At this point, the possibility of a new ferry being in service by 2020 is extremely low. I have maintained 2020 as the nominal starting point because 2020 is the most up-to-date replacement year provided by Skagit County, and the actual replacement year remains indeterminate at this point, based on the lack of funding. I acknowledge that PSE's CO_2 emissions rate is somewhat higher in the early 2020s, which slightly biases the electric ferry's lifetime CO_2 reduction downward. See: Skagit County. "Ferry Concept Design Work Currently Underway." Skagit County Ferry Replacement News. 2017-10. Available [2020-02-20]: https://www.skagitcounty.net/PublicWorksFerry/Documents/newsletter/newsletter1017.pdf

[117] See Section 3.6.1.4 in the Concept Design Report and Section 5.2 in the Transportation System Assessment.

[118] These costs have been adjusted to 2020 dollars by the Consumer Price Index (endnote 110). Washington Utilities and Transportation Commission. "Social Cost of Carbon." N.d. Available [2019-12-19]: https://www.utc.wa.gov/regulatedIndustries/utilities/Pages/SocialCostofCarbon.aspx

[119] Exhibit 24 was created from the resources listed below. Where prices were not in 2020 dollars, I adjusted them by the Consumer Price Index (U.S. urban average, endnote 110).

- State and federal social costs of carbon are taken from endnotes 110 and 111 respectively.
- The electric ferry's carbon abatement cost is based on the calculations of annual CO_2 savings in Appendix D and the CO_2 discount/escalation rate provided by: Washington Utilities and Transportation Commission. "Social Cost of Carbon." 2019-08-29. Available [2019-11-19]: https://www.utc.wa.gov/regulatedIndustries/utilities/Pages/SocialCostofCarbon.aspx
- The abatement costs of general actions are taken from the maximum cost estimates in Table 2 in: Kenneth Gillingham (Yale University) et al. "The Cost of Reducing Greenhouse Gas Emissions." Journal of Economic Perspectives. 32(4), 2018. Available [2019-09-17]:

https://pubs.aeaweb.org/doi/pdfplus/10.1257/jep.32.4.53
(In Table 2 of this paper, the "dedicated battery-electric vehicle subsidy" is at the bottom of the list, because it is the option with the highest minimum abatement cost.)

- The abatement costs of PSE consumer options are calculated as follows:

Variable	Quantity	Unit	Page	Source
CO2 reduction	400	lb	n/a	https://www.pse.com/green-options/Renewable-Energy-Programs/carbon-balance-for-home
Reduction cost	4	USD	n/a	Ibid.
CO2 reduction'	0.2	t	138	Lindeburg. Engineering Unit Conversions. 2009.
Abatement cost	**22.0**	**USD/t**	**n/a**	**Reduction cost / reduction' (PSE Offsets)**
Variable	**Quantity**	**Unit**	**Page**	**Source**
CO2 reduction	10,595	lb	n/a	https://www.pse.com/green-options/Renewable-Energy-Programs/green-power
Reduction cost	120	USD	n/a	Ibid.
CO2 reduction'	4.8	t	138	Lindeburg. Engineering Unit Conversions. 2009.
Abatement cost	**25.0**	**USD/t**	**n/a**	**Reduction cost / reduction' (PSE Green Power)**
Variable	**Quantity**	**Unit**	**Page**	**Source**
CO2 reduction	6,358	lb	n/a	https://www.pse.com/green-options/Renewable-Energy-Programs/solar-choice
Reduction cost	240	USD	n/a	Ibid.
CO2 reduction'	2.9	t	138	Lindeburg. Engineering Unit Conversions. 2009.
Abatement cost	**83.2**	**USD/t**	**n/a**	**Reduction cost / reduction' (PSE Solar Only)**

- The abatement costs of energy actions are based the first paper referenced below, assuming a 30% capacity factor for wind and a 20% capacity factor for solar, based on the second and third papers referenced below. PSE presently has opportunities for both coal and gas transition options, so I provided both transition abatement costs for reference.
  - See Figure 1 in: Philip Hanser et al. (The Brattle Group). "Re-evaluating the Implied Cost of CO_2 Avoided by Clean Energy Investment." The Electricity Journal. 30, 2017. Available [2019-12-19]: https://www.bu.edu/ise/files/2016/01/Re-evaluating-the-implied-cost-of-CO2-avoided-by-clean_2017_The-Electricity-.pdf
  - See Figure 5 in: Walter Short et al. (National Renewable Energy Laboratory). Regional Energy Development System (ReDS). Technical Report NREL/TP-6A20-46534. 2011-12. Available [2019-12-22]: https://www.researchgate.net/publication/255198388_Regional_Energy_Deployment_System_ReEDS
  - See Figure 38 in: Ryan Wiser et al. (U.S. Department of Energy). 2018 Wind Technologies Market Report. 2019-08. Available [2019-12-22]: https://www.energy.gov/sites/prod/files/2019/08/f65/2018%20Wind%20Technologies%20Market%20Report%20FINAL.pdf

[120] Skagit County. "Skagit County Climate Change and Sustainability Initiative." N.d. Available [2020-01-03]: https://www.skagitcounty.net/Departments/Sustainability

[121] If Skagit County insists upon reducing CO_2 emissions through the purchase of electrical equipment, then renewable generation projects are likely to be among the most cost-effective options today within those constraints. However, at some point, the intermittency of renewable energy will prevent it from further replacing more stable types of generation capacity until hours-long and days-long energy storage become an integral part of the grid. For this and other reasons, short-term peaking batteries are becoming popular subjects of research and development in the green energy sector. For example, see:

- National Renewable Energy Laboratories. "Could Batteries Provide Peaking Capacity on the Grid?" 2019-07-10. Available [2020-02-09]: https://www.nrel.gov/news/program/2019/could-batteries-provide-peaking-capacity-on-the-grid.html

- Wesley Cole et al. (National Renewable Energy Laboratories). Cost Projections for Utility-scale Battery Storage. 2019-07-10. Available [2020-02-09]: https://www.nrel.gov/docs/fy19osti/73222.pdf

[122] Puget Sound Energy. "Green Direct Energy Partnership." N.d. Available [2020-02-20]: https://www.pse.com/green-options/Renewable-Energy-Programs/green-direct

[123] The quotation is taken from the first citation. The second citation offers examples of projects with single-digit abatement costs per metric ton.

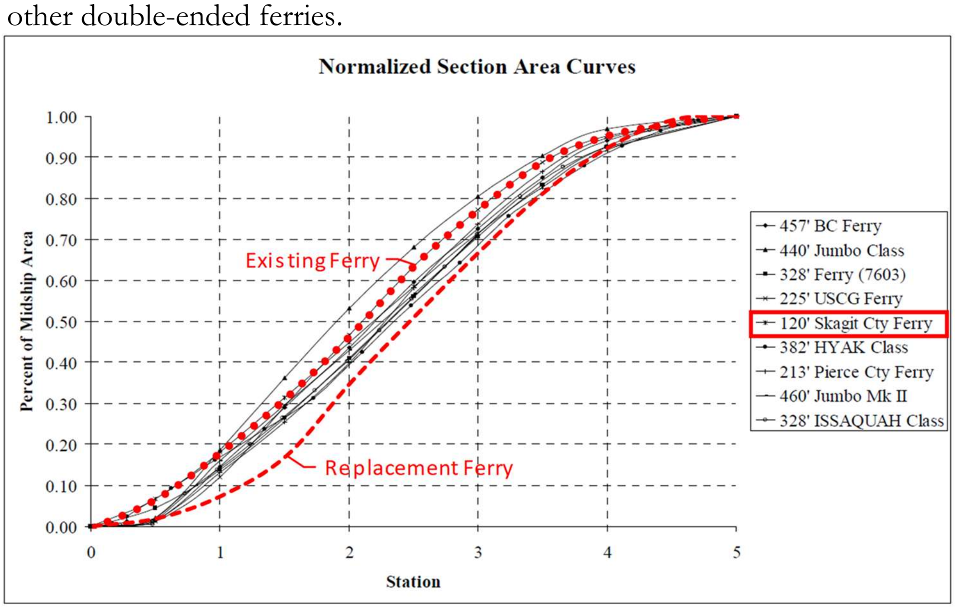
- Second Nature. "Purchasing Carbon Offsets FAQs." N.d. Available [2020-01-25]: https://secondnature.org/climate-action-guidance/purchasing-carbon-offsets-faqs/#verify
- Cool Effect. "Carbon Pollution Reduction." N.d. Available [2020-01-25]: https://www.cooleffect.org/content/projects

[124] According to *Ampere*'s class registry, the hull material is steel. The vessel's class society also considers it a "light craft," so the steel designation may be a typo. I have allowed the article to take precedence because it seems to contain detailed knowledge about the design process. See: Det Norske Veritas – Germanischer Lloyd. "*Ampere*: DNV GL Class Register." N.d. Available [2019-11-08]: https://vesselregister.dnvgl.com/VesselRegister/vesseldetails.html?vesselid=33075

[125] See Series "WSF 130" in Figure 5 in: John Waterhouse, P.E. (Elliott Bay Design Group). "50 Years of Double-ended Ferry Design." N.d. Available [2016-02-28]: https://www.ebdg.com/wp-ebdg-content/uploads/2016/07/JWW-50-Years-of-Double-Ended-Ferry-Design-Web.pdf

[126] Refining and optimizing to improve one aspect of hull performance usually involves some degree of compromising on many other aspects. For example, optimizing the hull shape for minimal resistance in the ahead-astern direction could increase the hull's resistance in side currents, among many other side-effects. A good optimization approach usually includes constraints and sensitivity checks, to make sure that the compromises are known and acceptable.

The figure below is Figure 4 in John Waterhouse's paper (endnote 125). It shows normalized sectional area distributions for many double-ended ferries built in the past several decades, with station on the horizontal axis and sectional area divided by midship area on the vertical axis. I highlighted the existing Guemes ferry (included in the original figure) and added the replacement Guemes ferry (based on Figure 11 in the CDR). **Relative to most ferries, the existing Guemes ferry has more volume distributed toward its ends, especially its extreme ends. Relative to most ferries, the replacement Guemes ferry has substantially less volume distributed toward its ends.** Computer optimization tends to pull volume away from the ends, which could increase the extent to which the replacement Guemes ferry is an outlier relative to other double-ended ferries.



There may be some practical reason why *Guemes*'s hull is shaped somewhat differently from the hulls of contemporary double-ended ferries. It would be reassuring to know what that reason was, and whether that reason still matters, before committing to a significant change in hull shape.

127 Calculations are as follows. It appears that the energy consumed by the automatic docking system may have been included in the calculation, but I cannot find it explicitly called out.

Variable	Quantity	Unit	Page	Source
Energy without	194.39	kWh/RT	A-6	CDR
Energy with	170.29	kWh/RT	A-6	CDR
Enegy reduction	12%			With / without - 1

128 See Section 4.1.3 in the Transportation System Assessment.

129 In Appendix A, I explain why I assume that the ratio of ship battery capacities between the 28- and 32-car ferries also represents the ratio of energy consumption (since energy consumption for the 28-car ferry is not publicly available). Per Table 2 of the 28-car Options Cost Estimate, the battery capacity at comparable design maturity points decreased from 1,050 kWh to 800 kWh, a reduction of 1 – (800 ÷ 1,050) = 24%.

130 Charles Mann delivers a TED talk in which he characterizes the polarization of opinions around tackling climate change as a dichotomy between "wizards" (people who believe technology is the solution) and "prophets" (people who believe lifestyle changes are the solution). Mann argues that both solutions must be pursued cooperatively. See: Charles Mann. "How will we survive when the population hits 10 billion?" TED. Available [20219-11-18]: https://www.youtube.com/watch?v=rmfzwwrCrrU

131 Here are some articles on impactful behavioral modifications:

- Centers for Disease Control and Prevention. "Sustainable Lifestyle." 2018-05-03. Available [2020-01-23]: https://www.cdc.gov/sustainability/lifestyle/index.htm
- Justin Rowlatt (British Broadcasting Corporation). "Climate Change: Big Lifestyle Changes Are the Only Answer." 2019-10-11. Available [2020-01-23]: https://www.bbc.com/news/science-environment-49997755
- Diego Arguedas Ortiz (British Broadcasting Corporation). "Ten Simple Ways To Act on Climate Change." 2018-11-04. Available [2020-01-23]: https://www.bbc.com/future/article/20181102-what-can-i-do-about-climate-change
- World Wildlife Federation. "Ten Things You Can Do To Help Save Our Planet." N.d. Available [2020-01-23]: https://www.wwf.org.uk/thingsyoucando
- Mary Cappelletti (Cascadia Climate Connection). "Top Sustainable Lifestyle Changes, Discussed and Simplified." 2019-01-18. Available [2020-01-23]: http://cascadiaclimateaction.org/top-sustainable-lifestyle-changes-discussed-and-simplified/
- Rosie McCall. "Five Easy Lifestyle Changes That Could Help Tackle Climate Change." Newsweek. 2019-09-20. Available [2020-01-23]: https://www.newsweek.com/lifestyle-changes-tackle-climate-change-1460462
- Gretchen Brown (Rewire). "Four Easy Lifestyle Changes To Be More Green in 2019." 2019-04-04. Available [2020-01-23]: https://www.rewire.org/our-future/easy-lifestyle-changes-be-more-green/

132 In the recent ferry operations survey, 57% of us supported adding ferry runs at noon, 36% of us supported adding ferry runs in the evenings, and 32-41% of us supported adding runs later into the night. See: Skagit County. "Guemes Ferry Operations & Service Survey." 2019. Available [2019-11-02]: https://www.publicinput.com/4955

133 In endnote 43, the ferry is estimated to make 8,718 round trips annually, including a 4% allowance for double runs. This works out to an average of 24 round trips per day. One additional run per day would increase energy consumption, and therefore emissions, by 1/24, or 4%.

[134] Calculations are as follows:

Variable	Quantity	Unit	Page	Source
RT Seattle to Ferry Lot	162.4	mi	n/a	Round-trip downtown SEA per Google Maps; Sea-Tac round-trip is 188.6 mi
CO2 from Gasoline	0.404	kg/mi	n/a	https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle
Car CO2 per SEA RT	65.61	kg/RT	n/a	RT Seattle to Ferry Lot x CO2 from Gasoline
Ferry CO2 Svgs/Xing	23.83	kg/Xing	n/a	CO2 savings per one-way crossing per Appendix D (avg. of 2020-2060 forecast).
Drive CO2 Equivalent	**2.8**	**Xings**	**n/a**	**Car CO2 per SEA RT / Ferry CO2 Svgs per Xing**

[135] Calculations are as follows:

Variable	Quantity	Unit	Page	Source
Forest CO2 Absorption	850	kg/yr/ac	n/a	https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references
Homesite Size	0.25	ac	n/a	Estimate of average clearcut for new homesite.
Lost CO2 Absorption	**213**	**kg/yr**	**n/a**	**Forest CO2 Absorption x Homesite Size**
Annual Propane	480	therms	n/a	Estimate based on actual bills for 1,600-sf second home.
Propane CO2 Rate	6.31	kg/therm	n/a	https://www.eia.gov/environment/emissions/co2_vol_mass.php (One therm is 100,000 Btu.)
Annual Propane CO2	**3,027**	**kg/yr**	**n/a**	**Annual Propane x Propane CO2 Rate**
Annual Electricity	1,200	kWh	n/a	Estimate based on actual bills for 1,600-sf second home.
Electricity CO2 Rate	0.232	kg/kWh	n/a	Ferry environmental impact calculations; average of 2020-2060 forecast
Annual Electric CO2	**278**	**kg/yr**	**n/a**	**Annual Electricity x Electricity CO2 Rate**
Annual Driving	1,664	mi/yr	n/a	10x RT from downtown Seattle. Route prescribed by Google Maps.
Driving CO2 Rate	0.404	kg/mi	n/a	https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle
Annual Driving CO2	**672**	**kg/yr**	**n/a**	**Annual Driving x Driving CO2 Rate**
Total Annual CO2	**4,190**	**kg/yr**	**n/a**	**Lost CO2 Absorption + Annual Propane CO2 + Annual Electric CO2 + Annual Car CO2**
Ferry CO2 Svgs per RT	47.66	kg/RT	n/a	CO2 savings per round-trip per Appendix D (avg. of 2020-2060 forecast).
House CO2 Equiv. (RT)	**87.9**	**RT/yr**	**n/a**	**Total Annual CO2 / Ferry CO2 Svgs per RT**
Average Daily RT	23.9	RT/day	n/a	Average ferry round-trips per day per Appendix D.
House CO2 Equiv (day)	**3.7**	**days/yr**	**n/a**	**House CO2 Equiv. (RT) / Average Daily RT**

[136] Calculations are as follows:

Variable	Quantity	Unit	Page	Source
Idling CO2	0.588	g/s	1	https://afdc.energy.gov/files/u/publication/which_is_greener.pdf
Idling time	600	s	n/a	Assume 10 min
CO2 per car idling	0.35	kg	n/a	Idling CO2 x idling time
Cars idling	20,000		n/a	Assume 10% of cars in each direction at 100k RT/y (200k one-way/yr)
Annual CO2	7.1	t	n/a	CO2 per car idling x cars idling
Ferry CO2 Svgs per RT	47.66	kg/RT	n/a	CO2 savings per round-trip per Appendix D (avg. of 2020-2060 forecast).
Idling in RTs	148	RT	n/a	Annual CO2 x 1000 t/kg / Ferry CO2 Svgs per RT
Average Daily RTs	23.9	RT/day	n/a	Average ferry round-trips per day per Appendix D.
Idling in days	**6.2**	**day**	**n/a**	**Idling in RTs / average daily RTs**

[137] This is an excerpt from a response to: Skagit County. "Guemes Ferry Replacement Survey." 2017. Available [2019-10-15]: https://publicinput.com/1970

[138] International Maritime Organization. Resolution MSC.337(91): Adoption of the Code on Noise Levels Onboard Ships. 2012-11-30. Available [2019-10-15]: http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Documents/MSC%20-%20Maritime%20Safety/337(91).pdf

[139] See Section 4.6 in the CDR.

[140] Glosten. Guemes Island Ferry Replacement: Concept General Arrangement. Rev. –, 2017-12-11. Available [2018-06-02]: https://www.skagitcounty.net/PublicWorksFerryReplacement/Documents/designreport/1c_Concept%20Design%20Drawings%20-%20GA.pdf

[141] "The Coast Guard realizes that reducing noise levels generally becomes increasingly more difficult on smaller vessels." See: "NVIC 12-82: Recommendations on Control of Excessive Noise." 1982-06-02. Available [2020-02-16]: https://www.dco.uscg.mil/Portals/9/DCO%20Documents/5p/5ps/NVIC/1982/n12-82.pdf

[142] Allegro Abramo (Oregon Public Broadcasting). "Puget Sound Is Getting An Orca-Friendly, All-Electric Ferry." 2017-08-23. Available [2019-10-20]: https://www.opb.org/news/article/puget-sound-is-getting-an-orca-friendly-all-electric-ferry/

[143] Office of Naval Research. A Summary of Underwater Acoustic Data: Part V, Background Noise. 1954-07. Available [2019-11-11]: https://apps.dtic.mil/dtic/tr/fulltext/u2/105841.pdf

[144] See:

- Ocean Studies Board (National Academy of Sciences). Ocean Noise and Marine Mammals. 2003. Available [2019-12-06]: https://www.ncbi.nlm.nih.gov/books/NBK221262/pdf/Bookshelf_NBK221262.pdf
  https://www.mmc.gov/wp-content/uploads/hildebrand.pdf
- John Hildebrand (Scripps Institution of Oceanography). "Sources of Anthropogenic Sound in the Marine Environment." 2004. Available [2019-12-06]: https://www.mmc.gov/wp-content/uploads/hildebrand.pdf

[145] University of Rhode Island et al. "Ship Quieting Technologies." Discovery of Sound in the Sea. N.d. Available [2020-01-25]: https://dosits.org/animals/effects-of-sound/moderate-or-eliminate-the-effects-of-human-activities/ship-quieting-technologies/

[146] See Figure 1, Figure 2, Section 3.1, and Section 3.5 in the CDR.

[147] Generally speaking, in the range of conditions in which propellers are designed to operate, cavitation increases with propeller blade loading, and a more lightly loaded blade is less efficient. The introduction to the paper cited here is publicly available for free, and it is probably a sufficient explanation for most readers. Mikael Grekula (SSPA). "The Never-ending Battle with Propeller Cavitation." 2010. Available [2020-01-27]: https://www.sspa.se/sites/www.sspa.se/files/field_page_files/hl50-10_cavitation_battle.pdf

[148] The author of the first resource below observed that summer noise levels could be three decibels higher as a result of increased recreational boat traffic. See:

- Jim Laughlin (Washington State Department of Transportation). Compendium of Background Sound Levels for Ferry Terminals in Puget Sound. 2015-05. Available [2019-12-06]: https://www.wsdot.wa.gov/sites/default/files/2017/06/27/Env-Noise-MonRpt-WSFBackgroundSoundLevels.pdf
- National Oceanic and Atmospheric Administration. "2011 Tidal Current Predictions: 6645: Rosario Strait." 2011. Available [2019-12-22]: https://tidesandcurrents.noaa.gov/get_predc.shtml?year=2011&stn=6645+Rosario%20Strait&secstn=Guemes+Channel,+west+entrance&sbfh=%2D0&sbfm=21&fldh=%2D0&fldm=33&sbeh=%2D1&sbem=24&ebbh=%2D0&ebbm=36&fldr=0.8&ebbr=1.1&fldavgd=095&ebbavgd=255&footnote=

[149] Underwater sound pressure is measured in decibels (dB) referenced to one micropascal. Sound pressure in air is referenced to 20 micropascals. The decibel scale is logarithmic. See: Robert Sherman et al. (Federation of American Scientists). "Underwater Acoustics." 1998-12-05. Available [2020-01-25]: https://fas.org/man/dod-101/sys/ship/acoustics.htm#conversion

[150] Measurements of underwater noise in open oceans are available in these documents:

- Joseph Haxel (Oregon State University) et al. "Ocean Sound Levels in the Northeast Pacific Recorded from an Autonomous Underwater Glider." Public Library of Science ONE 14(11). 2019-11-20. Available [2020-01-25]: https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0225325&type=printable
- Sharon Nieukirk (National Oceanic and Atmospheric Administration). "Understanding Ocean Acoustics." 2015-04-06. Available [2020-01-25]: https://oceanexplorer.noaa.gov/explorations/sound01/background/acoustics/acoustics.html
- University of Rhode Island et al. "Ocean Noise Variability and Noise Budgets." N.d. Available [2020-01-25]: https://dosits.org/science/advanced-topics/ocean-noise-variability-and-noise-budgets/

- Mark McDonald (Whale Acoustics) et al. "Increases in Deep Ocean Ambient Noise in the Northeast Pacific West of San Nicolas Island, California." Journal of the Acoustical Society of America 120. 2006-05. Available [2020-01-25]: https://asa.scitation.org/doi/figure/10.1121/1.2216565

[151] Each knot of current appears to raise the ambient underwater noise level by three decibels.

[152] Jim Laughlin (endnote 148) theorizes that the peak around 50 Hz in his frequency decompositions is caused by the propeller signatures of "larger vessels," including the state ferries that passed very closely to the hydrophone during low-rpm maneuvering. I wonder if the proximity of the ferries may have biased the result. See also Joseph Haxel et al. (endnote 150).

[153] Cascadia Consulting Group. Southern Resident Orca Task Force: Final Report and Recommendations. 2019-11. Available [2019-12-22]: https://www.governor.wa.gov/sites/default/files/OrcaTaskForce_FinalReportandRecommendations_11.07.19.pdf

[154] This report seems to have assumed that the vessels would not be operating on batteries. Its electric propulsion options involve using electricity to decouple the combustion device from the propeller shaft (viz. diesel electric propulsion). See: Hemmera Envirochem. Vessel Quieting Design, Technology, and Maintenance Options for Potential Inclusion in EcoAction Program Enhancing Cetacean Habitat and Observation Program. 2016-04-19. Available [2019-12-22]: https://www.portvancouver.com/wp-content/uploads/2017/01/Vessel-Quieting.pdf

[155] Contrast the propulsion efficiency of geared diesel (93%, Exhibit 46 in Appendix D) with the propulsion efficiency of all-electric in diesel hybrid mode (83%, Exhibit 47 in Appendix D). The efficiency of the geared diesel option includes the efficiency of a gearbox. Most large commercial ships have no gearbox; the propeller shaft is coupled directly to a low-speed diesel engine's output shaft to minimize losses.

[156] See page 176 in: Howard Marks. The Most Important Thing. 2011.

[157] I do not recall offhand which interview it was. It was within the past three years.

[158] See Exhibit 48 in Appendix D.

[159] Rebecca Matulka (U.S. Department of Energy). "The History of the Electric Car." 2014-09-15. Available [2019-11-14]: https://www.energy.gov/articles/history-electric-car

[160] Public Broadcasting Service. "Timeline: History of the Electric Car." 2009-10-30. Available [2019-11-14]: https://www.pbs.org/now/shows/223/electric-car-timeline.html

[161] For an explanation of the limitations of electric cars and the ongoing importance of internal combustion engines, see: Engineering Explained. "Why Gas Engines Are Far from Dead." 2020-02-05. Available [2020-02-09]: https://www.youtube.com/watch?v=Hatav_Rdnno

[162] Mark Reuss (Cable News Network). "GM President: Electric Cars Won't Go Mainstream Until We Fix These Problems." 2019-11-25. Available [2019-11-25]: https://www.cnn.com/2019/11/25/perspectives/gm-electric-cars/index.html

[163] Patrick Hertzke et al. (McKinsey and Company). "Expanding Electric-vehicle Adoption Despite Early Growing Pains." 2019-08. Available [2019-11-12]: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/expanding-electric-vehicle-adoption-despite-early-growing-pains

[164] Glosten. Guemes Island Ferry Replacement: Engineer's Cost Estimate. Rev. –, 2017-11-30. Available [2018-07-16]: https://www.skagitcounty.net/PublicWorksFerryReplacement/Documents/designreport/2c_Engineers%20Cost%20Estimate.pdf

[165] Chris Downes (NC Machinery). Telephone call with Brent Morrison regarding the cost of EPA Tier 3 and Tier 4 propulsion engines. 2019-10-09.

[166] Caterpillar. Performance Data: EM0270. 2013-08-23.

[167] Glosten. Guemes Island Ferry Replacement: Engineer's Cost Estimate. Rev. –, 2017-11-30. Available [2018-07-16]: https://www.skagitcounty.net/PublicWorksFerryReplacement/Documents/designreport/2c_Engineers%20Cost%20Estimate.pdf

[168] See page A-2 in the Concept Design Report.

[169] I have attended ferry committee meetings at which the question arises whether the cost of emergency repairs should be applied to the capital budget or the operational budget. Handbook 135 (endnote 79) offers a basic distinction between repair costs and capital replacement costs in Section 4.2.1. On page SA-2, it places the adjective "routine" in parentheses before the word "repairs."

[170] The calculation is as follows: $1 - 1.03^{-18} = 41\%$.

[171] The calculation is as follows: $1 - 1.02^{-18} = 30\%$.

[172] A 40-year design life is assumed in Section 4.2 in the Transportation System Assessment.

[173] Note the increasing ridership and capacity expectations in Figures 1 to 4 in the Vessel Capacity Study.

[174] See Section 4.5.3 of NIST Handbook 135 (endnote 79).

[175] Calculations were made based on the recent valuation reports listed below:

- Commercial Marine Service. M/V *Guemes* Condition & Valuation Report. 2012-11-08.
- Commercial Marine Service. M/V *Guemes* Condition & Valuation Report. 2014-11-17.
- Commercial Marine Service. M/V *Guemes* Condition & Valuation Report. 2015-10-26.
- Commercial Marine Service. M/V *Guemes* Condition & Valuation Report. 2017-05-10.
- Delphi Maritime. M/V *Guemes* Condition & Valuation Report. 2019-07-31.

[176] See the "Value Methodology" section in any of the reports by Commercial Marine Service.

[177] See the valuations on pages 2 and 3 of the Delphi report.

[178] Philip Lurie et al. (Institute for Defense Analyses). A Handbook of Cost Risk Analysis. 1993-04. Available [2019-11-19]: https://apps.dtic.mil/dtic/tr/fulltext/u2/a267253.pdf

[179] See Figure 1 in: Department of Energy. Cradle to Grave Lifecycle Analysis of Vehicle and Fuel Pathways. 2014-03-21. Available [2019-10-02]: https://www.hydrogen.energy.gov/pdfs/14006_cradle_to_grave_analysis.pdf

[180] Asea Brown Boveri. "Equipment Efficiency Estimates." N.d.

[181] U.S. Environmental Protection Agency. "Energy Star Guide to Buying More Energy Efficient Distribution Transformers." 2017-09-27. Available [2019-09-25]: https://www.energystar.gov/sites/default/files/asset/document/Transformers%20Buyer%27s%20GuideFinal10-16-17.pdf

[182] U.S. Energy Information Administration. "Frequently Asked Questions." 2019-12-31. Available [2020-02-08]: https://www.eia.gov/tools/faqs/faq.php?id=105&t=3

[183] See the following resources:

- U.S. Energy Information Administration. "Carbon Dioxide Emissions Coefficients." 2016-02-02. Available [2019-10-02]: https://www.eia.gov/environment/emissions/co2_vol_mass.php
- U.S. Energy Information Administration. "Table 8.1: Average Operating Heat Rate for Selected Energy Sources." N.d. Available [2019-10-02]: https://www.eia.gov/electricity/annual/html/epa_08_01.html
- U.S. Energy Information Administration. "Emissions by Plant and by Region." 2018-12-26. Available [2019-10-02]: https://www.eia.gov/electricity/data/emissions/
- Puget Sound Energy. "Our Diversified Electricity Supply." 2018-10. Available [2019-10-02]: https://www.pse.com/pages/energy-supply/electric-supply

[184] Puget Sound Energy. Environmental, Social, and Governance Report. 2019-01. Available [2019-10-02]: https://www.pse.com/-/media/PDFs/Our-Ethics-and-Goals/7056_ESG_Report.pdf

[185] Washington State Department of Commerce. "Energy Independence Act (I-931)." 2017. Available [2019-10-02]: https://www.commerce.wa.gov/growing-the-economy/energy/energy-independence-act/

[186] Washington State Department of Commerce. "Clean Energy Transformation Act." 2017. Available [2019-10-02]: https://www.commerce.wa.gov/growing-the-economy/energy/ceta/

[187] Puget Sound Energy. "PSE's Carbon Reduction Plan." N.d. Available [2019-10-02]: https://www.pse.com/pages/carbon-reduction-plan

[188] See Figures 4-6 and 6-16 in the IRP (endnote 115).

[189] Section 3.6 in the Concept Design Report states an assumed ferry life of 40 years. A start date of 2020 is given in: Skagit County. "Ferry Concept Design Work Currently Underway." Skagit County Ferry Replacement News. 2017-10. Available [2020-02-20]: https://www.skagitcounty.net/PublicWorksFerry/Documents/newsletter/newsletter1017.pdf

[190] On 2019-10-03, I asked PSE's IRP team to comment on my findings. PSE confirmed receipt by the correct department on 2019-10-10, but as of publication, it has not responded.

[191] Caterpillar. "Performance Data: EM0270." 2013-08-23.

[192] Union of Concerned Scientists. Cleaner Cars from Cradle to Grave. 2015-11. Available [2019-10-02]: https://www.ucsusa.org/sites/default/files/attach/2015/11/Cleaner-Cars-from-Cradle-to-Grave-full-report.pdf

[193] The charter is presently under revision. The existing and proposed charters are below.

- Guemes Island Ferry Committee. "Proposed GIFC Charter Amendments 2020." 2020-02-05. Available [2020-02-23]: http://gifc.octopia.com/pages/455169/Proposed-Charter-Amendments-2020/
- Guemes Island Ferry Committee. "Draft Ferry Committee Charter." 2009-12-21. Available [2020-02-23]: http://gifc.octopia.com/pages/3675