Rethinking Web for Affordability and Inclusion

Ihsan Ayyub Qazi†, Zafar Ayyub Qazi†, Ayesha Ali¶,
Muhammad Abdullah†, Rumaisa Habib†
†Department of Computer Science, ¶Department of Economics
Lahore University of Management Science (LUMS), Pakistan

ABSTRACT

Today's Web remains too expensive for many Internet users, especially in developing regions. Unfortunately, the rising complexity of the Web makes affordability an even bigger concern as it stands to limit users' access to Internet services. We propose a novel framework and fairness metric for rethinking Web architecture for affordability and inclusion. Our framework provides systematic guidelines for adapting Web complexity based on geographic variations in mobile broadband prices and income levels. Preliminary evaluation shows the resulting architecture can achieve a better balance between Web quality and affordability while preserving user privacy.

CCS CONCEPTS

• **Information systems** → **World Wide Web**;

KEYWORDS

Web, Affordability, Inclusion, User Privacy

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1 INTRODUCTION

The Web is widely considered as an enabler for development and socioeconomic mobility [11, 15, 16, 25]. Yet, it remains too expensive for many Internet users, especially in developing regions. A World Bank survey carried out in 11 emerging countries found that a median of 48% of respondents had difficulty paying for their mobile data usage, and 42% restrict the amount of data they use [12].

In 2018, the UN Broadband Commission for Sustainable Development set the target for affordable broadband services to be less than 2% of monthly Gross National Income (GNI) per capita. According to the International Telecommunication Union (ITU), 84 developing countries do not meet this target for a 1.5 GB data-only mobile broadband plan.[1] The average price in 48 countries is between 2–5% of GNI per capita[2] while in 16 countries the price exceeds 10% of GNI [22].

Concurrently, we are observing a steady increase in Web complexity. For example, the median mobile webpage size has increased from 145 KB to 1918 KB in the last decade; a 13× increase [20]. Partly, this growing complexity stems from the fact that Web's design does not take into account affordability. Thus, such a trend can reduce users' Web accesses and make Internet services less affordable, especially for users in developing regions. On the other hand, while mobile broadband prices have reduced in the last few years, the decrease has been slow. For example, between 2019 and 2020, the median price for mobile broadband services reduced by only 0.2 percentage points [22]. This calls for designing solutions that can make the Web affordable by taming the complexity of the Web experienced by users from regions with high broadband prices relative to income levels.

Recent initiatives for reducing Web complexity in developing countries (e.g., Free Basics [3, 29], Google Web Light [6], Discover [27]) face two key challenges (see Table 1): (i) they target an extreme design point for affordability, which comes at the cost of substantial reduction in webpage quality. For example, Web Light reduces the median webpage size by 12× but can break the functionality of pages, thereby making them unusable [30]. Similar to Web Light, Free Basics pages cannot have JavaScript (JS), iframes, large images, and other rich content and (ii) they rely on proxy-based solutions that break the end-to-end principles of TLS [27, 29, 30],which has raised significant data privacy and network neutrality

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[1] Countries are benchmarked according to the price of the cheapest data-only mobile broadband plan available domestically, with a minimum of 1.5 GB monthly data allowance and a technology of 3G or above. Mobile plans involving voice and data (at least 500 MB) were more expensive [21, 22]
[2] We use GNI to refer to GNI per capita throughout the rest of the paper.

Services	Example Data-Saving Mechanisms
Free Basics [3, 29]	Webpages cannot have JavaScript, large images, iframes, videos, Flash, and Java applets
Web Light [6, 30]	Removes all JS (except with scripts within an iframe for ads), resizes large images, and converts external CSS into inline CSS, replaces video with an image
Facebook Discover [27]	Limits responses to 1 MB, removes images or reduces resolution, and removes video, audio and other rich content
FlyWheel [9]	Compresses images (works only for HTTP traffic)

Table 1: Some example services being used in developing countries for reducing data charges. They target an extreme design point for affordability at the cost of substantial reduction in QoE and use proxy-based solutions that have led to privacy and net-neutrality concerns.

concerns and has led to even banning of services in some countries [24, 31].

In this work, we make a case for rethinking Web design around affordability and inclusion. To this end, we present, AW4A (Affordable Web For All) that addresses the above challenges and achieves a better balance between affordability and webpage quality by relying on two key principles: (i) Web frameworks should explicitly account for affordability constraints in their design and (ii) website operators should determine Web content adaptations to preserve user privacy and meet their business needs.

AW4A provides a systematic way for incorporating affordability constraints in Web design by relying on a new fairness metric, PAW (Price Adjusted Web access), which captures how equitable and affordable *Web accesses* are across regions with different mobile broadband prices and income levels. PAW is used to come up with different Web complexity targets, which AW4A uses to generate multiple versions of a website with different complexities. The decision about which low complexity versions to generate is taken by the website operators, who are offered choices to select from different resource optimizations for achieving a target complexity. While AW4A offers a webpage quality that meets the affordability target in a region, it also offers a choice to users to view a higher quality webpage if they wish to do so.

By offering more equitable Web accesses through a differentiated service offering, AW4A can bring more users online and increase access by constrained users, which in turn can lead to increased revenues for website operators. For example, our analysis shows that reducing the average webpage size by 1.5× can allow 10%–15% of the countries to meet the affordability target for Web accesses, which is achievable without significantly reducing page quality. Moreover, reducing complexity can make it viable for mobile service providers to offer smaller data plans, as users can derive more value from the same data budget.

Finally, AW4A has synergies with the increasing trend of Lite apps (e.g., Facebook Lite, Skype Lite), which are being designed for entry-level smartphones that are prevalent in developing countries [2, 26]. These apps are designed by the content providers themselves, have smaller sizes, and reduced functionality that meets the goals of the service providers. Altogether, we make the following contributions:

- We make a case for adapting Web complexity based on geographical variations in broadband prices and average income levels across regions.
- We propose a fairness metric, PAW, which captures how equitable average webpage accesses are across countries.
- We present AW4A; a framework for offering lower complexity Web versions and carry out an evaluation using a cross-country analysis of 8 developing countries.
- We highlight the quality-access trade-off using a simple model and show via a small-scale user study with 25 participants that users can observe significant utility gain by trading off webpage quality for increased Web accesses.

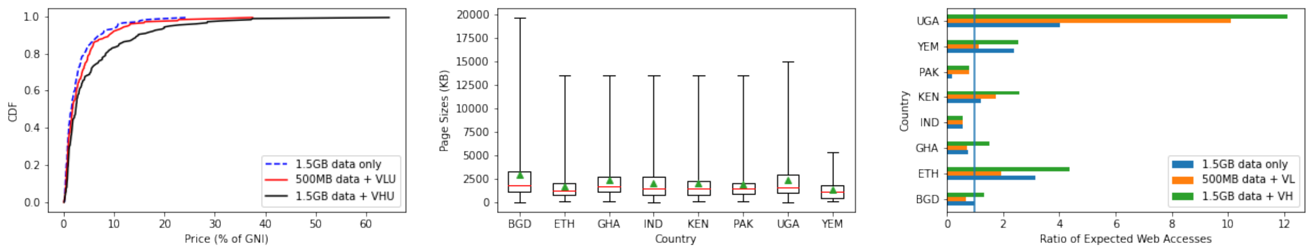
2 MOTIVATION

Using data from ITU, we first analyze the variations in mobile broadband prices across 176 countries [22]. We then analyze the Web complexity across a sample of 8 developing countries by measuring the sizes of landing pages of Alexa top 100 websites accessed from each of these countries [1].[3]

2.1 Distribution of Mobile Broadband Prices

Figure 1a shows the distribution of prices (normalized by GNI) for three mobile broadband plans across 176 countries: These plans, defined by ITU, include: (i) a 1.5 GB data only plan (DO), (ii) a hybrid plan comprising 500 MB of data and voice low-usage (DVLU), and a hybrid plan with 1.5 GB of data and voice high-usage (DVHU). First, we observe that there are large variations in mobile broadband prices across countries ranging from 0.09% (Luxembourg) to as high as 65% (Malawi) for a DVHU plan. Second, 42%, 45%, and 55% of the countries do not meet the UN Broadband Commission's affordable target price of 2% for DO, DVLU, and DVHU plans, respectively. The lack of affordability of mobile Internet has directly translated into large usage and consumption gaps in developing countries. For example, in South Asia alone, 64% of the population do not use the Internet despite having at least 3G coverage, reflecting a large usage gap and a survey carried out in 11 emerging countries found that a median of 48 percent of respondents had difficulty paying for their mobile data usage [12].

[3] We use WebPageTest [8] and a popular entry-level mobile device, Nokia 1, to fetch these pages.



(a) Broadband Prices **(b) Webpage Sizes** **(c) PAW index**

Figure 1: (a) Mobile broadband prices as a percentage of GNI per capita across 176 countries for three plans. 42%–55% of the countries do not meet the affordability target of 2% across the plans, (b) distribution of landing webpage sizes for Alexa top 100 websites from 8 developing countries: Bangladesh (BGD), Ethiopia (ETH), Ghana (GHA), India (IND), Kenya (KEN), Pakistan (PAK), Uganda (UGA), and Yemen (YEM). Green triangles represent the average sizes and (c) ratio of mean Web accesses across 8 countries relative to the affordability target and the mean global page size of 2.39 MB based on Alexa top 100 websites globally. The vertical line at x=1 shows the ratio at the global benchmark level and bars exceeding 1 do not meet the target.

2.2 Webpage Complexity Across Regions

The growing complexity of the Web has led to steady increases in webpage sizes, which in turn, has increased the cost per access to a website. For example, in the last five years, the median mobile page size has increased from 943 KB to 1918 KB, an increase of 103% [4]. Due to the differences in the popularity of websites across countries, we expect the average webpage size observed by users to also differ across countries. Thus, we collect the sizes of landing pages of Alexa top 100 websites accessed from 8 developing countries with different average broadband prices, including Bangladesh, Ethiopia, Ghana, India, Kenya, Pakistan, Uganda, and Yemen. We find that the webpage sizes differ significantly across countries with mean sizes varying from 1375 KB ($\sigma = 1149$ KB) in Yemen to 2972 KB ($\sigma = 3564$ KB) in Bangladesh (see Figure 1b). These variations in webpage sizes (both across countries as well as within countries) directly impact the data usage and the number of websites a user can access before running out of a data plan.

3 DESIGN

We now present the design of our framework, AW4A. First, we introduce a new fairness metric for affordability and analyze the distribution of Web accesses available to users across countries. This analysis provides Web complexity targets for the framework. Second, we carry out a What-If analysis to determine the possible reduction in page sizes with different resource optimizations. Finally, we discuss potential mechanisms for achieving different complexities.

3.1 Fairness Metric for Web Accesses

To capture the differences in average webpage sizes, broadband prices and income levels across regions as well as enable comparisons against a common benchmark, we present a new fairness metric for affordability, which we call the PAW index. $\mathtt{PAW}_i$ captures the reduction needed in the average webpage size in a region i to achieve the affordability target for Web accesses and is computed as follows:

$$\mathtt{PAW}_i = \frac{P_i}{P_T} \times \frac{W_{i,avg}}{W_{global}} \qquad (1)$$

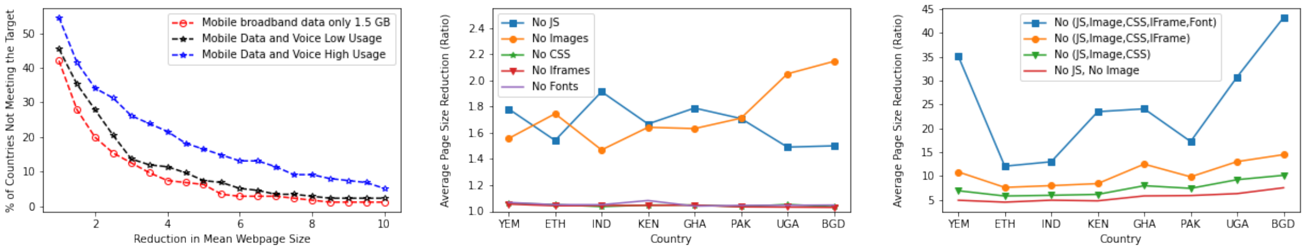
where P_T is average price target set by UN's Broadband Commission, which currently stands at 2%, P_i is the average mobile broadband price in region i as a percentage of GNI, $W_{i,avg}$ is the average webpage size in region i, and W_{global} is the average webpage size globally. $\mathtt{PAW}_i > 1$ for region i if the number of Web accesses do not meet the affordability target and $\mathtt{PAW}_i \leq 1$ if it does. For example, if $W_{i,avg} = 1.5$ MB, $P_i = 5\%$ in region i, $W_{global} = 2.39$ MB, and $P_T = 2\%$, then $\mathtt{PAW}_i = 1.57$.

The number of accesses, A_T, available at the target affordable price is given by D/W_{global}, where W_{global} is the average global webpage size. Therefore, the maximum number of Web accesses, A_i, available in region i to meet the affordability target is $(P_T/P_i) \times (D/W_{avg})$, where D is the data plan limit (e.g., 1500 MB). In order to equalize accesses (i.e., $A_i/A_T = 1$), we require the average webpage size to be set to $W^T_{avg} = (P_T/P_i) \times W_{global}$.

We use W_{global} to benchmark webpage sizes according to the prevailing global quality of webpages. Thus, if in region i the average page size is already lower than the average global page size, than a smaller reduction in page quality is required to equalize access relative to another region j, where the page size is larger. Therefore, despite the inherent trade-off between accesses and page quality, with this benchmarking we are able to minimize the differences in quality across regions while equalizing access.

3.2 Web Accesses Across Regions

Based on the mobile broadband price and the average webpage size in each of the eight countries, we find the expected



(a) Affordability-size trade-off **(b) Single resource type** **(c) Multiple resource types**

Figure 2: (a) Percentage of countries that meet the target number of Web accesses for different mobile plans as a function of the reduction in the average webpage size in a country. (b) possible webpage size reductions with removals of one resource type from the pages, and (c) possible webpage size reductions with removals of multiple resource types from the pages.

number of Web accesses a user can afford at the target price of 2% before running out of a monthly mobile plan (see Figure 1c). Using these we compute the `PAW` index. First, observe that 6 out of 8 countries do not meet the target Web accesses for at least one of the mobile plans. The maximum `PAW` index for the DO plan is 4.5 whereas for DVHU, it is 12. This suggests that offering lower complexity versions (e.g., 1.5×, 2×, and 4.5×) of popular websites in these countries can bring many users within the affordability Web access budget. Second, within developing countries where an average user meets the target Web accesses, differences in income levels make it challenging for low-income users to meet this target. For example, the price of mobile broadband for users in the bottom income quintile in Pakistan is as much as 2.5% of the GNI compared to the average price of 0.96%. Thus, a viable way of making the Web more affordable is to offer multiple low complexity versions of Websites while still providing users the option to view a high quality page.

Web accesses across 176 countries. Figure 2a shows the percentage of countries meeting the Web accesses target as a function of the reduction in mean webpage size in a country.[4] Observe that reducing the average page size by 1.5× allows 10%–15% countries to meet the target accesses whereas a 3× reduction will bring 28%–32% countries within the target across the three mobile plans. These insights can serve as useful guides for modulating website complexity.

3.3 What-if Complexity Analysis

Using the features of Alexa top 100 websites accessed in each of the 8 developing countries, we carry out a What-If analysis on the possibilities of achieving the website complexity targets based on the `PAW` index.

Individual resource types. Figure 2b shows the reduction in page sizes upon removing all elements of a single resource type (e.g., images, JS, CSS, and iframes). We find that since JS and images contribute the most bytes to webpages (former contributing 33%–47% and latter 32%–53%), removing them provides the largest reductions in page sizes ranging from 1.5×–1.9× with JS and 1.5×–2.1× with images.

Multiple resource types. Next, we consider removals of multiple combinations of resource types. Figure 2c shows that removing all JS and images from Alexa top 100 pages in all countries can reduce page size from 4.5×–7.5× and removing all five resource types reduces page size from 13×–43×, essentially resulting in a text-only webpage.

The above results provide an estimate of the maximum Web complexity reductions. While results show a significant reduction in Web complexity, these may come at the cost of a considerable decrease in page quality. Our What-if analysis also suggests that 2.3×–3.8× reductions in the average page sizes are possible across the eight countries by reducing the total bytes due to images and JS by 50%. Next, we build on these insight to explore different resource optimizations.

3.4 Achieving the Target Website Complexity

Given the `PAW` index value in region i, we can achieve various target complexities by applying different resource optimizations. Table 2 lists some mechanisms for optimizing images, JS, CSS, iframes, and fonts.

As different optimizations impact page quality differently, we assign priorities to optimization based on their impact on quality (e.g., reducing image quality is more preferred than image removals). Given a target size for a webpage, we then apply optimizations until the target is met. Depending on the desired page complexity, different trade-offs emerge. For example, reducing complexity by 6× may not be possible for some pages without substantially degrading page quality. However, a complexity reduction of 1.5× is achievable in many cases without degrading quality (§4.2).

Summary. Our analysis in this section suggests there are opportunities for achieving a better trade-off between affordability and page complexity than approaches (e.g., Web Light, Free Basics, and Discover) that offer a one-size-fits-all low complexity version at a substantial reduction of page quality.

[4] We do not have data for webpages accessed from all 176 countries. Therefore, we use the global mean webpage size of 2.39 MB for all countries.

Resource	Example Optimizations
Image	Transcoding to size efficient formats (e.g., Webp, AVIF) [19], reducing image quality, image resizing (e.g., to their CSS attributes width and height) [23], image compression [9], image removal [30]
JS	Removing unused JS [32], using lighter JS frameworks [28], removing non-critical JS [14], and compression (e.g., using `gzip`)
CSS	Resizing images embedded by CSS [23], convert external CSS to inline CSS [30], minification, and compression [17]
WebFont	Removing optional metadata (e.g., font hinting, kerning), font subsetting, font compression (e.g., EOT and TTF formats) [18]
Iframes	Minification, compression [17] and removal [3]

Table 2: Some example optimizations for different Web resources.

4 ANALYSIS & EVALUATION

4.1 Quality–Access Analysis

We can achieve equity in accesses by trading off webpage size, which serves as a proxy for webpage quality. We capture this tradeoff through the Cobb-Douglas utility function [13, 33].

Let $U_i(W, A)$ by the utility of user i, where A is the expected number of website accesses available to the user and W is the average webpage size in the region. We assume that U_i is a concave function in both A and W. In particular,

$$U_i(W, A) = a \cdot log(W) + b \cdot log(A) \quad (2)$$

where a and b are positive constants which denote the weight of each attribute in user's utility. The trade-off between W and A depends on the slope of this function, which is equivalent to the number of units of W that the user is willing to give up to get an additional A, while keeping utility constant. Mathematically, this is equal to the ratio of the partial derivatives of U_i with respect to A and W, that is, $\frac{a/W}{b/A}$.

We can also show that for U_i to increase when W decreases and A increases, the following condition must hold: $\frac{b/A}{a/W} > \frac{dW}{dA}$. This condition implies that for a user to experience a utility gain, the willingness to give up quality to get more access must be greater than what the user would have to give up as a result of equalizing access across regions. Furthermore, users can have differing willingness to give up quality for access, depending on their current consumption of W and A, which reflects variations in the price of broadband and income levels. Thus, the utility gain (or loss) from equalizing access will also vary based on these features.

4.2 User Study

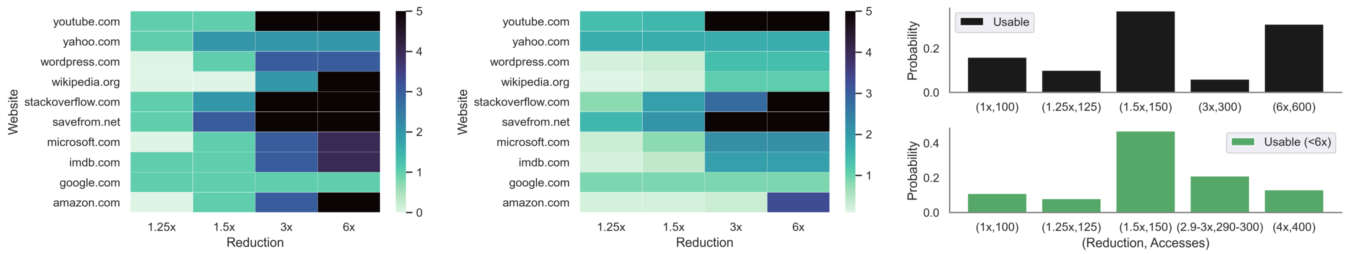
To quantify the quality-access trade-off, we conducted a small-scale user study with 25 participants for which an Institutional Review Board (IRB) approval was obtained. Users were recruited from a university campus via email and included students, staff and faculty. A survey typically lasted between 10-15 minutes. The median age in our sample was 24 years and the median income was between USD 315 and 474 per month. To put this in perspective, the minimum monthly wage in the country of the user study was USD 123. The average monthly expenditure on mobile broadband subscription as a ratio of the monthly income in the sample was 3.8%, which is greater than the affordability target of 2%.

Webpage complexity and optimizations. We selected 10 websites that were common in the Alexa top 100 websites list across the 8 developing countries.[5] For each website, we created four low complexity versions of the landing pages that were 1.25×, 1.5×, 3×, and 6× smaller in size than the original version by applying different Web optimizations. While all webpages remained usable for up to 1.5× page size reduction, 8 remained functional with 3× reduction, and 5 pages with 6× reduction. Figure 3a shows the heatmap of optimizations, with lighter shades representing ones with little or no quality impact and darker shares representing larger quality impact, as a function of page size reduction. We observe for some websites 1.25× is achievable by just converting images into WebP format, while for other websites 1.5× reduction can be achieved by reducing image quality between 25%–75%. However, for several websites, we had to remove all images and some/all external JS to achieve 6× page size reduction.

Visual perception of pages. We showed 5 versions of each website to every participant and asked them to rate page look similarity (scale: 0–10) and page content similarity (scale: 0–10). Figure 3b shows the heatmap of average of page look and content similarity ratings (normalized to a maximum score of 5). While almost all websites were rated to be quite similar to the original version at 1.5× reduction, some exhibited a good degree of similarity even at 6× reduction (e.g., wikipedia.org). However, some websites (e.g., youtube.com, savefrom.net) resulted in stark dissimilarities at large page size reductions due to removal of visually important resources.

Quality-Access trade-off. Figure 3c shows the distribution of user choices for different combinations of webpage quality (indicated by the size reduction factor) and number of monthly Web accesses available to similar quality websites. For the 5 websites that remained usable with 6× reduction, participants chose options (1.5×,125) and (6×,600) with probability 0.37 and 0.31, respectively (upper plot). This indicates that some users preferred 600 accesses despite 6× lower page quality whereas others preferred a higher quality pages even if it meant smaller Web accesses. For websites that were

[5]These include {google, yahoo, microsoft, imdb, wordpress, amazon, stackoverflow, youtube}.com, wikipedia.org, savefrom.net.



(a) Optimizations-Reduction **(b) User Ratings** **(c) Quality-Access Trade-off**

Figure 3: (a) The heatmap shows the optimizations needed to achieve different page size reductions in terms of their impact on webpage quality on a scale of 0–5. 0 refers to optimizations that cause little or no change in quality (e.g., transcoding images into WebP format), 1 refers to reducing image quality or removing some external JS, 2 corresponds to removing all images, 3 to removing all images, some external JS, and the page usable, 4 to removing all images and external JS (page is usable), and 5 to removing all images and JS (page is unusable). (b) heatmap of user ratings on page look and content similarity with the original page (lighter shades reflect greater similarity), and (c) distribution of participant choices for page size reduction and Web accesses.

not usable with 6× reduction, the most popular combination was (1.5×,150) with a significant number of users choosing combinations with more than 2.9× quality reductions. These results suggest that a significant fraction of users are likely to observe a utility gain by trading off page quality for more Web accesses, as indicated in §4.1.

5 INCENTIVES FOR STAKEHOLDERS

We now discuss incentives for different stakeholders for using a AW4A-like framework.

Website operators. AW4A gives the option to website operators to offer their services at reduced quality, thereby creating a differentiated service offering. This new market for reduced quality services can appeal to existing users who are data constrained and new users who were previously unable to afford these services. The increase in the number of Web accesses and users visiting a website will likely increase advertising revenue due to higher click-through rates. Finally, website operators have the freedom to determine the extent to which they want to differentiate their services (by reducing quality). They can base their decisions on profit and social motives.

Mobile network operators. Data consumption is highly sensitive to market prices and service affordability [12]. An affordable Web framework can make it attractive for mobile service providers to offer smaller data plans, as users can derive more value from the same number of MBs. This can bring more users online, who were previously shut out from the market for these Web services due to affordability constraints. In the medium to long term, prices can decline if there is an increase in supply of mobile data services by network operators, for example, due to investments in new infrastructure to improve capacity and reach.

Users. Our framework will offer a choice to users between different page qualities rather than exclusively offering a separate class of Web content to users. Thus, users can have more accesses if they are willing to trade off page quality. As we expand the affordable consumption choice set for these users, their utility should increase.

6 DISCUSSION AND FUTURE WORK

Usability. When offering multiple versions of a website, an important consideration is *usability*. One approach is to offer a version based on the average price in a user's country and provide a link to a higher quality version (e.g., similar to [6]).
User-driven customization. An extreme design point involves offering a complexity customized page to each user based on their income. However, users may not be comfortable sharing this information. Another option is to offer website versions based on large geographical units within countries where such data is available (e.g., using census data).
Non-landing pages and caching. We only considered landing pages in our work, which are more frequently requested by users, but the complexity of inner pages will also impact data usage [10]. We did not consider (i) scenarios involving a user to log into a website and (ii) the impact of client-side caching, which reduces data usage for repeated visits to a website. In the future work, we plan to incorporate these aspects in our evaluation.
Video. While rich multimedia content, such as video, has not been the focus of works on developing countries that target affordability, we believe future trends in video compression (e.g., WebM [7], VP9 [5]) and customization of video resolutions will likely make it plausible to serve lite video content. This remains part of our future work.

7 CONCLUSION

This paper makes a case for rethinking Web for affordability and inclusion by adapting Web complexity based on geographical variations in broadband prices and average income levels. To this end, we proposed a new fairness metric based on the equitability of Web accesses across regions and a framework for generating low complexity versions of websites.

REFERENCES

[1] [n. d.]. Alexa - The top 500 sites on the web. ([n. d.]). http://www.alexa.com/topsites/countries.
[2] [n. d.]. Android Go. ([n. d.]). https://www.android.com/versions/go-edition/.
[3] [n. d.]. Free Basics Platform. ([n. d.]). https://developers.facebook.com/docs/internet-org.
[4] [n. d.]. http archive. ([n. d.]). https://httparchive.org/.
[5] [n. d.]. VP9 Overview. ([n. d.]). https://developers.google.com/media/vp9.
[6] [n. d.]. Web Light: Faster and lighter mobile pages from search. ([n. d.]). https://support.google.com/webmasters/answer/6211428?hl=en.
[7] [n. d.]. WebM: an open web media project. ([n. d.]). https://www.webmproject.org/.
[8] [n. d.]. WebPageTest. ([n. d.]). https://www.webpagetest.org/.
[9] Victor Agababov, Michael Buettner, Victor Chudnovsky, Mark Cogan, Ben Greenstein, Shane McDaniel, Michael Piatek, Colin Scott, Matt Welsh, and Bolian Yin. 2015. Flywheel: Google's Data Compression Proxy for the Mobile Web. In *Proceedings of the 12th USENIX Symposium on Networked Systems Design and Implementation (NSDI 2015)*.
[10] Waqar Aqeel, Balakrishnan Chandrasekaran, Anja Feldmann, and Bruce M. Maggs. 2020. On Landing and Internal Web Pages: The Strange Case of Jekyll and Hyde in Web Performance Measurement. In *Proceedings of the ACM Internet Measurement Conference (IMC '20)*. Association for Computing Machinery, New York, NY, USA, 680–695. https://doi.org/10.1145/3419394.3423626
[11] World Bank. 2021. Digital Development. (2021). https://www.worldbank.org/en/topic/digitaldevelopment.
[12] World Bank. 2021. World Development Report 2021 : Data for Better Lives. (2021). https://openknowledge.worldbank.org/handle/10986/35218.
[13] Jeff Biddle. 2012. Retrospectives: The Introduction of the Cobb-Douglas Regression. *Journal of Economic Perspectives* 26, 2 (May 2012), 223–36. https://doi.org/10.1257/jep.26.2.223
[14] Moumena Chaqfeh, Yasir Zaki, Jacinta Hu, and Lakshmi Subramanian. 2020. JSCleaner: De-Cluttering Mobile Webpages Through JavaScript Cleanup. In *Proceedings of The Web Conference 2020 (WWW '20)*. Association for Computing Machinery, New York, NY, USA, 763–773. https://doi.org/10.1145/3366423.3380157
[15] Raissa Fabregas, Michael Kremer, and Frank Schilbach. 2019. Realizing the potential of digital development: The case of agricultural advice. *Science* 366, 6471 (2019). https://doi.org/10.1126/science.aay3038 arXiv:https://science.sciencemag.org/content/366/6471/eaay3038.full.pdf
[16] World Economic Forum. 2020. The Global Social Mobility Report 2020 Equality, Opportunity and a New Economic Imperative. (2020). http://www3.weforum.org/docs/Global_Social_Mobility_Report.pdf.
[17] Ilya Grigorik. 2019. *Optimizing Encoding and Transfer Size of Text-Based Assets*. https://cutt.ly/EmqpXJU.
[18] Ilya Grigorik. 2019. *Reduce WebFont Size*. https://web.dev/reduce-webfont-size/.
[19] Katie Hempenius. 2018. *Fast load times*. https://web.dev/serve-images-webp/.
[20] HTTPArchive. [n. d.]. *Report: State of the Web*.
[21] ITU. 2019. *ITU price data collection rules*. https://www.itu.int/en/ITU-D/Statistics/Documents/ICT_Prices/ICT%20Price%20Basket%20rules_E.pdf.
[22] ITU. 2020. *Measuring Digital Development: ICT Price Trends 2020*. https://www.itu.int/en/ITU-D/Statistics/Pages/ICTprices/default.aspx.
[23] Conor Kelton, Matteo Varvello, Andrius Aucinas, and Ben Livshits. 2021. BrowseLite: A Private Data Saving Solution for the Web. In *Proceedings of the Web Conference 2021 (WWW '21)*. Association for Computing Machinery, New York, NY, USA, 305–316. https://doi.org/10.1145/3442381.3449885
[24] Brian Kondracki, Assel Aliyeva, Manuel Egele, Jason Polakis, and Nick Nikiforakis. 2020. Meddling Middlemen: Empirical Analysis of the Risks of Data-Saving Mobile Browsers. In *2020 IEEE Symposium on Security and Privacy (SP)*. 810–824. https://doi.org/10.1109/SP40000.2020.00077
[25] Martin Mühleisen. 2018. The Long and Short of The Digital Revolution. *Finance and Development* 55 (06 2018), 4.
[26] Usama Naseer, Theophilus A. Benson, and Ravi Netravali. 2021. WebMedic: Disentangling the Memory-Functionality Tension for the Next Billion Mobile Web Users. In *Proceedings of the 22nd International Workshop on Mobile Computing Systems and Applications (HotMobile '21)*. Association for Computing Machinery, New York, NY, USA, 71–77. https://doi.org/10.1145/3446382.3448652
[27] Lucy Pei, Benedict Salazar Olgado, and Roderic Crooks. 2021. Market, Testbed, Backroom: The Redacted Internet of Facebook's Discover.. In *In CHI Conference on Human Factors in Computing Systems (CHI '21)*. 13. https://doi.org/10.1145/3411764.3445754
[28] Ihsan Ayyub Qazi, Zafar Ayyub Qazi, Theophilus A. Benson, Ghulam Murtaza, Ehsan Latif, Abdul Manan, and Abrar Tariq. 2020. Mobile Web Browsing under Memory Pressure. *SIGCOMM Comput. Commun. Rev.* 50, 4 (Oct. 2020), 35–48. https://doi.org/10.1145/3431832.3431837
[29] Rijurekha Sen, Sohaib Ahmad, Amreesh Phokeer, Zaid Ahmed Farooq, Ihsan Ayyub Qazi, David Choffnes, and Krishna P. Gummadi. 2017. Inside the Walled Garden: Deconstructing Facebook's Free Basics Program. *SIGCOMM Comput. Commun. Rev.* 47, 5 (Oct. 2017), 12–24. https://doi.org/10.1145/3155055.3155058
[30] Ammar Tahir, Muhammad Tahir Munir, Shaiq Munir Malik, Zafar Ayyub Qazi, and Ihsan Ayyub Qazi. 2020. Deconstructing Google's Web Light Service. In *Proceedings of The Web Conference 2020 (WWW '20)*. 884–893. https://doi.org/10.1145/3366423.3380168
[31] James Vincent. 2016. *Facebook's Free Basics Service has been banned in India. The Verge*. https://www.theverge.com/2016/2/8/10913398/free-basics-india-regulator-ruling.
[32] web.dev. 2020. *Remove unused JavaScript*. https://web.dev/unused-javascript/.
[33] Wikipedia. 2019. *Cobb–Douglas production function*. https://en.wikipedia.org/wiki/Cobb%E2%80%93Douglas_production_function.