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Making a virtue out of necessity: The effect of negative interest rates on bank cost efficiency

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ABSTRACT

Do negative interest rates affect banks' cost efficiency? We exploit the unprecedented introduction of negative policy interest rates in the euro area to investigate whether banks *make a virtue out of necessity* in reacting to negative interest rates by adjusting their cost efficiency. We find that banks most affected by negative interest rates responded by enhancing their cost efficiency. We also show that improvements in cost efficiency are more pronounced for banks that are larger, less profitable, with lower asset quality and that operate in more competitive banking sectors. In addition, we document that enhancements in cost efficiency are statistically significant only when breaching the zero lower bound, indicating that the pass-through of interest rates to cost efficiency is not effective when policy rates are positive. These findings hold important policy implications as they provide evidence on a beneficial second-order effect of negative interest rates on bank efficiency.

1. Introduction

In June 2014, the European Central Bank (ECB) was the first major central bank to undertake the unprecedented decision to cut its deposit facility rate (DFR) into negative territory.[1] Further cuts followed in September 2014, December 2015, and March 2016, each by 10 basis points (bps), until the DFR reached -0.5% in September 2019. With the primary aim of providing additional monetary stimulus, thereby contributing to price stability and supporting economic growth, the ECB's adoption of negative policy rates (NPRs) has been part of a wider credit-easing strategy to counter off substantial deflationary risk.[2]

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[1] The DFR is the interest rate that banks receive for depositing reserves with the Eurosystem overnight. Together with the interest rate on the main refinancing operations (MRO) and the rate on the marginal lending facility (MLF), the DFR represents a key interest rate set by the ECB Governing Council.

[2] In response to the severe effects of the 2008 global financial crisis, many central banks worldwide, began to experiment with a range of unconventional monetary policies, (i) including large-scale asset purchases (LSAPs) to increase asset prices and money supply; (ii) targeted asset purchases to impact the relative prices of selected assets; and (iii) forward guidance which aims at reducing the uncertainty about future policy rate paths.

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Besides the ECB, since 2012 the central banks of several European countries outside the euro area (Denmark, Hungary, Norway, Sweden and Switzerland) and Japan introduced Negative Interest Rate Policies (NIRP). However, NIRP effectiveness remains potentially controversial for several reasons (Ball et al., 2016; Bech and Malkhozov, 2016; Jobst and Lin, 2016). One of the main criticism is associated with the negative effects of NIRP on bank margins and profits as banks may be reluctant to impose negative rates on deposits because of the fear of losing their deposits base (Heider et al., 2019). Lower bank profitability can lead, in turn, to a contraction in lending supply and therefore impair the transmission mechanism of monetary policy under negative rates as well as the expansionary aim of central banks (Abadi et al., 2023). Further unintended consequences associated with NIRP, such as asset over-valuation and banks' tendency to assume excessive risk, can pose a risk to financial stability (Hong and Kandrac, 2022).

Banks may offset the potentially negative effects of NIRP on bank profitability in several ways. First, they could offset the contraction in net interest margins by increasing loan volumes. Second, they could boost non-interest income via raising fees and commissions and/or gains from holding a sizeable amount of held-for-trading fixed-income securities. Third, they may react to NIRP by increasing their holdings of riskier, higher-yielding assets. A growing strand of the literature has already focused on the different channels through which NIRP impacts the supply of bank credit to the real economy (Heider et al., 2019; Brown, 2020; Demiralp et al., 2021; Bottero et al., 2022; Arce et al., 2023; Eggertsson et al., 2024;) and bank profitability (Molyneux et al., 2019; Klein, 2020; Lopez et al., 2020; Altavilla et al., 2022). Other studies explored the way negative interest rates affect banks' risk-taking and the "reach-for-yield" behaviour (Bubeck et al., 2020; Bongiovanni et al., 2021; Hong and Kandrac, 2022), systemic risk (Nucera et al., 2017) and the usage of cash (Liñares-Zegarra and Willesson, 2021).

In this paper, we investigate a previously unexplored channel and put forward the hypothesis that NIRP-affected banks - i.e. banks with a greater reliance on deposits as a source of funding - strategically react to the detrimental repercussions of NIRP on their performance by improving their cost efficiency. In the spirit of Heider et al. (2019), by assuming that the behaviour of low- deposit banks offers the counterfactual for the behaviour of high-deposit banks, we compare the cost efficiency of euro area banks with different deposit-to-total assets ratios, before and after the ECB's adoption of NIRP.[3] Indeed, Fig. 1 reveals that deposit-based banks experienced greater contractions on margins and profits in comparison to banks less reliant on deposits. Therefore, we conjecture that negative rates have strengthened euro area banks' incentives to improve their efficiency to mitigate the adverse impact on their profitability. Furthermore, we explore whether the heterogeneity in balance sheet and market conditions, before the introduction of NIRP in 2014, influenced banks' incentives to enhance their cost structure.

We fill the gap in the extant literature on the effects of NIRP on banks by analysing the impact on cost efficiency, defined as the ability to generate the highest levels of desirable outputs (e.g. loans and other earning assets) with the lowest use of input (e.g. deposits and labour). In particular, we take a different perspective from the existing ones, which focus on the bank- lending and deposit channels, as well as the bank-balance sheet channel, as thoroughly discussed in Brown (2020). We exploit the ECB implementation of NIRP in mid-2014 and a comprehensive dataset of bank balance-sheet and profit and loss characteristics to investigate whether and to what extent euro area banks had to make a virtue out of necessity, therefore enhancing cost efficiency. We employ stochastic frontier analysis (SFA) to estimate banks' cost efficiency and a panel dataset of 1,130 banks from 17 euro area countries between 2011 and 2018. To test the hypothesis central to our study, we employ a difference-in-differences (DiD) econometric identification strategy where we compare the behaviour of banks with different deposit ratios around the introduction of policy rates below the zero lower bound (ZLB).

Our evidence suggests that NIRP-affected banks responded to the introduction of NIRP via improvements in their cost efficiency. We document greater incentives to enhance cost efficiency for banks that are larger, less profitable, with lower asset quality, weaker pre-NIRP lending growth and that operate in competitive banking sectors. Therefore, based on our findings, we can infer that (i) large banks have more room for *manoeuvres* on operating costs than smaller banks; (ii) banks that are less profitable, with lower asset quality and limited lending capacity face additional pressures to react to the negative effects of NIRP on profits; and (iii) competitive market conditions further compress banks' margins and profits in a negative interest rate environment, thereby pushing banks to enhance their cost efficiency. In addition, we document that enhancements in cost efficiency are statistically significant only when breaching the ZLB, indicating that the pass-through of interest rates to cost efficiency is not effective when policy rates are positive. These findings hold relevant implications for both financial stability and the transmission of the monetary policy. If NIRP-affected banks improve their cost efficiency, this may lead to higher profits with beneficial effects in terms of financial stability and monetary policy transmission as banks' lending decisions largely depend on retained earnings as a source of funding (Shin, 2016).

Our paper contributes to the existing literature in two main ways. First, we add to the growing strand of literature that analyses the impact of NIRP on the euro area banking sector and its specific transmission channels (Heider et al., 2019; Molyneux et al., 2019; Bubeck et al., 2020; Demiralp et al., 2021). In particular, to the best of our knowledge, we are the first to explore the effect of negative interest rates on banks' cost efficiency. Our evidence informs the ongoing debate on the implications of monetary policies below the ZLB. Second, we extend prior literature on efficiency in European banking (Maudos et al., 2002; Vander Vennet, 2002; Casu and Girardone, 2004; Bos and Schmiedel, 2007; Feng and Wang, 2018; Huljak et al., 2023), adding to the relatively limited evidence from recent years.

The remainder of the paper is organized as follows. Section 2 discusses the relevant literature. Section 3 provides the identification

[3] In our empirical settings, we consider high (low)-deposit banks those institutions with a deposit-to-total assets ratio above (below) the median value of the related distribution, pre-NIRP. As discussed in Heider et al. (2019), given that both these groups of banks are subject to the same deterioration in the economic conditions prompting the ECB's implementation of NIRP, their comparison allows to effectively isolate the banks' behaviour in response to the negative rates, thereby addressing the endogeneity concerns surrounding the monetary policy.

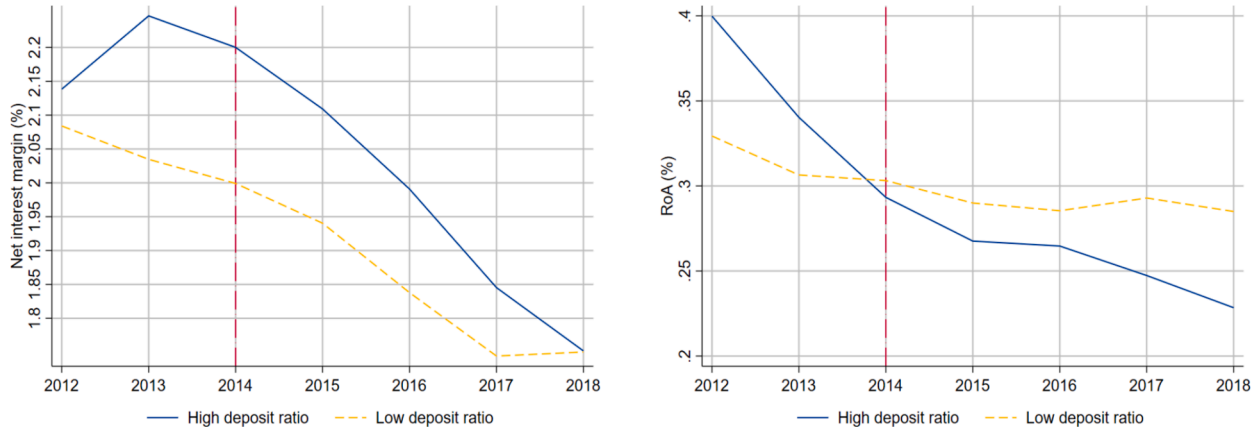

Fig. 1. Trends in banks' net interest margins and return on assets before and after NIRP.
This figure displays the trends in net interest margins and return on assets over the period 2012-2018 for high-deposit banks (blue solid line), i.e. banks relying mostly on deposits as a funding source, and low-deposit banks (dashed yellow line), i.e. banks holding fewer deposits. High-deposit and low-deposit ratios identify those banks that prior to the introduction of NIRP had a ratio of deposits to total assets above and below the median, respectively. The vertical dashed red line indicates the year of the introduction of NIRP (2014).

strategy and empirical methodology. Section 4 describes the sample and data. Sections 5 and 6 present the results and the robustness checks, respectively. Section 7 concludes and offers relevant policy implications.

2. NIRP, transmission channels and bank cost efficiency

The adoption of a NIRP implies charging banks for holding excess reserves at the central bank, thereby strengthening their incentives to expand lending in an attempt to reduce their reserve holdings. This is intended to produce positive effects for the real economy, such as greater loan supply and demand, resulting from reduced funding costs for both banks and borrowers.

While a standard reduction in policy rates has the potential to lower banks' funding costs and consequently results in higher bank net worth (due to the core maturity transformation performed by banks) and increased capability to lend, rate cuts leading to negative territory may produce different effects.[4] In particular, the pass-through of negative rates to customers might be limited for a number of reasons, especially in the short-term. For small-size retail deposits, banks might be reluctant to charge negative rates to avoid losing long-term customers, who could opt for holding cash or sovereign bonds and/or switching banks. Moreover, there could be legal and/or political constraints hindering the possibility of applying negative rates to retail deposits (Bubeck et al., 2020; Altavilla et al., 2022). Therefore, as discussed in several contributions (Eggertsson and Woodford, 2003; Correia et al., 2013), doubts are cast on the effectiveness of monetary policies below the ZLB.

Banks' ability to transfer negative rates to wholesale customers is somehow different. As demonstrated by Altavilla et al. (2022), sound banks that rely more on the wholesale market for funding, as opposed to high (retail)-deposit banks, tend to pass on negative rates to their corporate deposits and the degree of pass-through assumes greater strength as policy rates become more negative. Therefore, while a ZLB may exist for retail deposits, a different mechanism works in the case of corporate deposits when central banks move into negative territory, with the potential to generate a heterogeneous impact on high- and low-deposit banks.[5] In this respect, with policy rates turning negative, Eggertsson et al. (2024) document a reduced credit growth for Swedish banks relying more on deposit financing. Heider et al. (2019) find that euro area banks with more retail deposits reduce their lending and increase risk-taking. Molyneux et al. (2019) argue that banks in NIRP-adopter countries, which are more reliant on deposit funding, less capitalized and more interest income-oriented, reveal weaker lending.

Negative interest rates are transmitted via different channels, impacting both the asset and liability sides of banks' balance sheets. The overall effect of NIRP on banks' performance and, therefore, the balance between costs and benefits is uncertain and still subject to ongoing debate and research.[6] Negative rates may erode banks' profitability, mostly by compressing their net interest margin, given the difficulty of passing them to retail deposits. As discussed in the relevant literature (Nucera et al., 2017; Arce et al., 2023; Molyneux et al., 2019; Bubeck et al., 2020; amongst others), banks can compensate for the effects of negative rates by (i) increasing lending

[4] Reduced (albeit positive) policy rates also tend to increase the franchise value of banks with higher net worth, thereby limiting the incentives to assume extra risk Heider et al. (2019).

[5] Compared to corporate customers, retail (households) clients can easily withdraw their deposits, substituting them with cash (Eisenschmidt and Smets (2019)). Moreover, in the case of small deposits, usually, banks tend to charge additional fees rather than change interest rates (Altavilla et al., 2022)

[6] A recent strand of the literature explores the impact of a "negative-for-long" scenario on banks' key functions and behaviour (Arce et al., 2023; Stráský and Hwang, 2019; Brandão-Marques et al., 2021).

volumes; (ii) boosting fees and commissions (non-interest income); and (iii) taking extra risks.[7] However, the possibility to leverage these strategies strongly depends on specific features at the bank level, as well as factors characterising the overall banking sector and, more in general, the country where banks operate. In case of limited possibilities to enhance the non- interest income and if banks do not have sufficient risk-bearing capacity (i.e. bank capital), also functional to extend the loan supply, it is then likely to observe a fall in profits under negative policy rates.[8] In addition, and specific to the euro area banking context, the high levels of non- performing loans (NPLs) as a legacy of the global financial and sovereign debt crises weighed on banks' profitability, dragging on capital resources and further restricting the ability to grant new loans. As per Arce et al. (2023), less profitable banks, with lower capital strength, are left with fewer options to tackle the adverse effects of low (negative) interest rates. Also, while NIRP may induce bank balance-sheet (re) adjustments, there could exist points beyond which banks can no longer tolerate the squeeze of margins, especially for a prolonged period (Bech and Malkhozov, 2016).

In this paper, we aim to understand whether an unexplored strategy that euro area banks exploited to mitigate the effects of negative rates has been that of enhancing their cost efficiency. Given the squeeze in profit margins for deposit-based banks stemming from NIRP, we can reasonably expect, *ceteris paribus*, that NIRP-affected banks might have pursued the route of efficiency improvements to sustain profits. Unlike existing contributions, we focus on a different channel of monetary policy transmission to euro area banks, seeking to shed light on unexplored impacts of NIRP. Thus, the first hypothesis is as follows:

H1. *Ceteris paribus, did high-deposit euro area banks enhance their cost efficiency in response to the introduction of NIRP in June 2014?*

The need for banks to improve their cost efficiency following the introduction of NIRP depends also on banks' balance sheets and market conditions prior to NIRP. For instance, smaller banks engaging in relationship lending may incur higher monitoring costs, given that the "soft" information is the result of costly long-term relationships (Petersen and Rajan, 1994; Uchida et al., 2012; Bolton et al. 2016). Consequently, for smaller retail-oriented banks, it may be more difficult to react to NIRP by improving costs, for instance, by closing up branches. In addition, high-deposit banks that are less profitable may face additional pressure to improve their cost efficiency in comparison to more profitable institutions as low profitability impairs banks' ability to increase lending and risk-taking (Bongiovanni et al., 2021). Furthermore, banks with poorer asset quality may struggle to maintain profits by boosting their lending in a negative interest rate environment, hence being forced to adopt different strategies, including improving their cost structure. Banks with an already weaker credit growth prior to NIRP may face additional pressures to enhance their cost efficiency as negative rates may further limit their ability to increase loan volumes (Molyneux et al. 2020). Finally, in a negative interest rate environment, the degree of competition in the banking sector could represent an additional key factor in encouraging banks to work on their cost efficiency, given that a higher bank competition level can *de facto* amplify the contraction of the net interest margins (Molyneux et al., 2019). Our second hypothesis is accordingly as follows:

H2. *Do higher/lower incentives to enhance cost efficiency for high-deposit banks depend on the balance sheet and market conditions in place before the introduction of NIRP in June 2014?*

3. Identification strategy

3.1. Cost efficiency estimation

This study employs the SFA to generate cost efficiency scores for each bank in the sample under investigation, over the sample period between 2011-2018.[9] Specifically, we adopt a two-step procedure based on which the initially estimated efficiency scores obtained from the stochastic frontier are regressed, in a second step, on a selected set of explanatory variables. This approach enables us to examine the impact of NIRP on euro area banks' efficiency, while controlling for a number of bank-specific and country-level factors. As widely recognized in prior literature on cross-country samples (Beccalli, 2004; Gaganis and Pasiouras, 2013; Luo et al., 2016), there is the need to assume a common frontier as a benchmark necessary for the comparison of banks located in different countries. To this end, data across countries are pooled together and a common frontier is estimated.

3.2. Selection of inputs and outputs

We select the input and output variables of the cost frontier in line with the standard intermediation approach (e.g. Sealey and Linley, 1977; Maudos et al., 2002; Gaganis and Pasiouras, 2013; Chortareas et al., 2013). This stream of literature considers banks as financial intermediaries that turn inputs (*funds*, *physical capital*, and *labor*) into outputs (*loans* and *other profitable assets*). Three input prices are defined as: (i) the cost of borrowed funds (W1), measured as the interest expense divided by the total deposits; (ii) the cost of physical capital (W2), as proxied by the ratio of overhead expenses, net of personnel costs, and the fixed assets' book value; and (iii) the

[7] Furthermore, beneficial effects in terms of reduced loan-loss provisions, as a result of improved borrowers' capability to meet their obligations, can help to sustain profits.

[8] Especially in the case of less capitalized institutions, bank capital regulation can limit greater risk-taking in response to negative interest rates (Bongiovanni et al., 2021).

[9] For a comprehensive review of the importance of bank efficiency and the different approaches to measure it, see Hughes and Mester (2019).

cost of labour (W3), calculated as the ratio between personnel expenses and the number of employees. By following a common approach employed in the literature on bank cost efficiency Lozano-Vivas and Pasiouras (2010), Goddard et al. (2014), we employ as bank outputs: (i) loans (Q1) and (ii) other earning assets (Q2). Furthermore, in the spirit of Mester (1996), Altunbas et al. (2000) and Fiordelisi et al. (2011), amongst others, we include bank equity (EQUITY), as a quasi-fixed input, aimed at considering the different risk profiles of banks in the euro area. Berger and Mester (1997) consider bank equity as an additional source for lending and other earning assets, so the exclusion of this factor in the function could produce a scale bias in the inefficiency estimate and, in some cases, the cost of raising equity may be higher than that of collecting deposits. Moreover, we also include as an additional measure of bank riskiness, i.e. the Z-score, as in Altunbas et al. (2000) and Goddard et al. (2014).[10] Linear homogeneity restrictions are imposed by using the third input price (W3) to normalize all input prices and our dependent variable. Lastly, to account for technological changes during our sample period (Lensikn et al., 2008; Lozano-Vivas and Pasiouras, 2010), we include both linear and quadratic time trends (T and T^2, from T = 1 in 2011 to T = 8 in 2018) in our function.

3.3. Stochastic Frontier Analysis (SFA)

To estimate a bank's cost efficiency, we exploit a multiproduct translog function (Vander Vennet, 2002; Bos and Kool, 2006; Berger et al., 2009; Williams, 2012; Shamshur and Weill, 2019). Similarly to the existing academic literature, the multi-product translog function consists of a second-order Taylor expansion. The advantage is that the aforementioned function is characterized by wide flexibility in the evaluation of the efficiency frontier (Luo et al., 2016). By leveraging the previously defined input and output prices, the cost function is the following:

$$
\begin{aligned}
ln\left(\frac{Y_{it}}{W_3}\right) = {} & \alpha + \beta_1 ln(Q_1) + \beta_2 ln(Q_2) + \beta_3 ln\left(\frac{W_1}{W_3}\right) + \beta_4 ln\left(\frac{W_2}{W_3}\right)) + \beta_5 ln(EQUITY) + \\
& \beta_6 \frac{1}{2}(ln(Q_1))^2 + \beta_7 \frac{1}{2} ln(Q_1) ln(Q_2) + \beta_8 \frac{1}{2}(ln(Q_2))^2 + \beta_9 \frac{1}{2} ln\left(\frac{W_1}{W_3}\right)^2 \\
& \beta_{10} \frac{1}{2} ln\left(\frac{W_1}{W_3}\right) ln\left(\frac{W_2}{W_3}\right) + \beta_{11} \frac{1}{2} \left(ln\left(\frac{W_2}{W_3}\right)\right)^2 + \beta_{12} \frac{1}{2}(ln(EQUITY))^2 + \\
& \beta_{13} ln(Q_1) ln\left(\frac{W_1}{W_3}\right) + \beta_{14} ln(Q_1) ln\left(\frac{W_2}{W_3}\right) + \beta_{15} ln(Q_2) ln\left(\frac{W_1}{W_3}\right) + \\
& \beta_{16} ln(Q_2) ln\left(\frac{W_2}{W_3}\right) + \beta_{17} ln(EQUITY) ln(Q_1) + \beta_{18} ln(EQUITY) ln(Q_2) + \\
& \beta_{19} ln(EQUITY) ln\left(\frac{W_1}{W_3}\right) + \beta_{20} ln(EQUITY) ln\left(\frac{W_2}{W_3}\right) + \beta_{21} Trend + \\
& \beta_{22} \frac{1}{2} Trend^2 + \beta_{23} Trend\, ln\,(Q_1) + \beta_{24}\, Trend\, ln\,(Q_2) + \beta_{25} Trend\, ln\left(\frac{W_1}{W_3}\right) \\
& \beta_{26} Trend\, ln\left(\frac{W_2}{W_3}\right) + \beta_{27}{}^* ln(Z - score) + \upsilon_{i,t} + \nu_{i,t}
\end{aligned}
$$

where Y_{it} represents the total cost (TC) of production of bank i at time t. Q1 and Q2 are the bank outputs (i.e., loans and other earning assets respectively). W1, W2 and W3 are the input prices (i.e., the cost of borrowed funds, the cost of physical capital, and the cost of labour). EQUITY is the financial capital. The Z-score captures bank riskiness.[11] T is the time trend. The estimated input-oriented efficiency score ($Costeff_i$) ranges between 0 and 1 for bank i. Following the SFA method, the closer the bank is to the theoretical best practice frontier representing full efficiency (100%), the more efficient it is, in the sense that its outputs cannot be further expanded without increasing its inputs. A bank with an efficiency score below 100% is relatively inefficient, suggesting that it can attain its current output level by employing fewer inputs.

3.4. Econometric framework

In the second stage of our analysis, we use a DiD specification to explore the effect of NIRP on bank efficiency scores. In the spirit of Heider et al. (2019), our identification strategy relies on comparing bank efficiency scores of euro area banks with different deposit ratios, after the introduction of NIRP in June 2014. Equation (2) presents our baseline model:

$$Costeff_{ijt} = \alpha_i + \beta(High - deposits_{ij}{}^* Post_t) + \sigma K_{ijt-1} + \tau_t + \epsilon_{it} \tag{2}$$

[10] In line with the approach adopted by Altunbas et al. (2000), and with the aim of limiting the loss of degrees of freedom, only the bank equity variable has been interacted with the outputs and the input prices.

[11] The Z-score indicates the distance from the insolvency of bank i at time t. More specifically, it indicates the number of standard deviations that a bank's profitability has to fall below the average for the bank to become insolvent. A high Z-score represents a greater level of bank stability.

$Costeff_{ijt}$ are the estimated cost efficiency scores for bank i in country j at time t.[12] α_i indicates bank-fixed effects employed to gauge time-invariant unobservable bank characteristics. $High - deposits_{ij}$ is a dummy variable that takes the value 1 if in 2013 (i.e. before NIRP), the average ratio of deposits to total assets of bank i located in a NIRP-affected country j was above the median, and 0 otherwise.[13] $Post_t$ is a dummy variable that assumes the value 1 after the introduction of NIRP, and 0 otherwise. Since NIRP was introduced on 5 June 2014, the related dummy variable ($Post_t$) assumes the value 1 from 2014 year-end onward. β is our coefficient of interest, which represents the average difference in cost efficiency between high-deposit and low-deposit banks after the introduction of NIRP. Based on our DiD setting, this coefficient provides indications about the direction of the effect, i.e., whether high-deposit banks improved their cost efficiency relative to low-deposit banks after NIRP, rather than a direct estimate of absolute efficiency levels.

K_{ijt-1} is a vector of lagged bank- and country-specific control variables used to capture cross-bank and cross-country heterogeneity over time. Specifically, we include the ratio of gross loans to total assets (LOANS), the logarithm of total assets (SIZE), the net income to total asset ratio (ROA), the total regulatory capital ratio (TOTCAP), the ratio of net interest income to operating income (INT_OP), the ratio of loan loss provisions to net interest income (LLP), the loan growth of gross loans (Loan_GR) and the Z-score, calculated as sum of ROA and the equity to total assets ratio divided by the country-level standard deviation of ROA (Zscore). Among the country-specific characteristics, we control for the inflation rate (INFLATION) and for the GDP growth (GDP_g). Control variables are lagged by one period in order to overcome possible endogeneity and simultaneity concerns.[14] τ_t indicates year fixed-effects employed to control for time-variant shocks affecting all banks during the sample period, thereby mitigating the potential bias in estimates of β. Robust standard errors (ϵ_{it}) are clustered at the bank-level.

The DiD method must satisfy suitability requirements if we apply it to determine the effect of NIRP on bank cost efficiencies. First, treatment assignment has to be exogenous with respect to bank efficiency. In our empirical setting, meeting this assumption seems reasonable as the implementation of NIRP is driven by the need to fuel below-target inflation and to tackle weak aggregate demand (IMF, 2017). Thus, influencing bank efficiency does not represent a policy aim. Second, according to Bertrand et al. (2004) and Imbens and Wooldridge (2009), the DiD approach is only valid under the restrictive assumption (i.e. the parallel trend assumption), whereby changes in the outcome variables in the timespan before the application of the treatment are similar for both the treatment (i.e. banks with an above-median level of deposit ratio) and the control group (i.e. banks with a below-median level of deposit ratio). Fig. 2 depicts the development of the outcome variable from 2011 to 2018, for both the treated and control groups. As evident, the level of bank cost efficiency for the two groups shares a comparable trend prior to the NIRP introduction, suggesting that the parallel assumption holds and, therefore, the validity of our empirical setting.

An additional threat to our econometric identification strategy arises from the existence of potential time-varying differences between the treatment and control groups. Indeed, while cross-sectional differences across banks are ruled out by the large set of control variables included in the model specification, as well as by bank fixed effects, one key identifying assumption is also the absence of time-varying differences across high-deposits and low-deposits banks. In this regard, Fig. 3 displays the deposit-to-total assets ratio in the post-NIRP period (2015-2018) for banks with a pre-NIRP (2013) above median deposit-to-total assets ratio (the treatment group) and banks with a pre-NIRP (2013) below median deposit-to-total assets ratio (the control group). As shown, the deposit-to-total assets ratio is fairly stable for the two groups of banks over the post-NIRP period, limiting the concerns that, for instance, high-deposit banks may have transitioned to the other group following the introduction of NIRP. This suggests that the deposit-to-total assets ratio tends to be sticky over time, further supporting the choice of low-deposit banks as a valid counterfactual for the behaviour of high-deposit banks.

4. Sample and Data

The dataset used in this analysis is a balanced bank-level panel data comprising 1,130 banks located in 17 euro area countries.[15] We consider banks with different institutional forms, namely bank-holding and commercial banks, cooperative banks and saving banks.[16] The data employed in the empirical analysis are gathered from multiple sources. With the aim of maximising the sample size, bank balance sheet and performance data are collected both from Moody's BankFocus and SNL Financial. This also allows ensuring greater consistency of the information provided and thereby minimising the impact of potential misreporting and outliers. The macroeconomic series are obtained from the World Bank (World Development Indicators).[17] Bank specific characteristics, sampled on an annual basis, are winsorized at the 1% and 99% levels to mitigate the influence of outliers.

Descriptive statistics for bank cost efficiency scores, bank balance sheet variables and macro-economic variables related to both the treatment and control groups, prior to and after the in- troduction of NIRP, are reported in Table 1. Panels A and D of Table 1 present

[12] In a robustness check, we also use the cost-to-income ratio as a alternative dependent variable.

[13] For robustness purposes, we provide variation to the baseline specification by either performing a DiD with two different continuous treatment variables or using quartiles, instead of the median, for the definition of the treated group (refer to Section 6 for further details).

[14] A correlation matrix provided in Table A in Appendix A suggests that correlation coefficients are relatively low. Multicollinearity issues should not impact our regression results.

[15] We excluded Latvia and Lithuania as they joined the euro area in 2014 and 2015, respectively.

[16] We follow the classification provided by BankFocus. Table B in Appendix A provides detail on the sample composition, both regarding the country where banks are located, as well as the bank specialization.

[17] BankFocus and SNL Financial cover financial statement data both at the consolidated and unconsolidated level. In our dataset, in order to avoid duplicate observations, we either include the unconsolidated data or the consolidated one, but without unconsolidated subsidiaries.

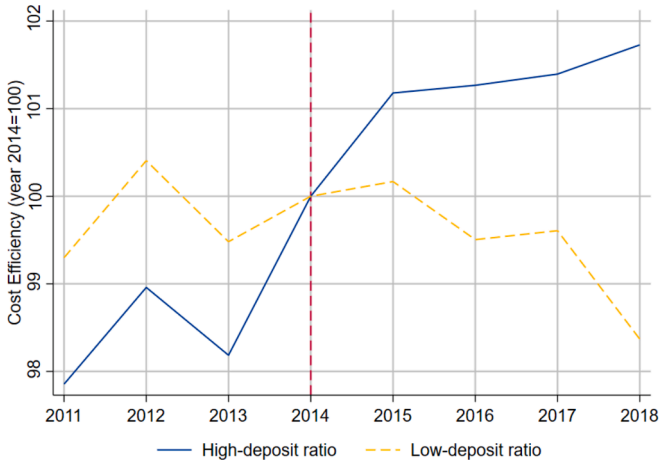

Fig. 2. Cost efficiency evolution before and after NIRP.
This figure shows the normalised trends (year 2014=100 index) of the average bank cost efficiency estimates for the group of banks that have a deposit-to-total assets ratio in 2013 above the median (our treatment group) and the control group over the period 2011-2018. High-deposit and low-deposit ratio identifies those banks that prior to the introduction of NIRP (2013) had a ratio of deposits to total assets above (blue solid line) and below (yellow dashed line) the median, respectively. Trends are normalised such that both variables take a value 100 in 2014. The red solid vertical line indicates the introduction of NIRP in 2014.

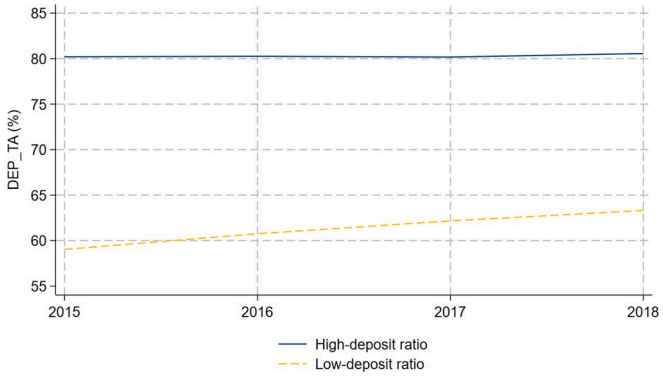

Fig. 3. Trends in banks' deposits to total asset ratio after NIRP.
This figure displays the trends in deposits to total assets ratio over the period 2015-2018 for high-deposit banks (blue solid line), i.e. banks relying mostly on deposits as a funding source, and low-deposit banks (dashed yellow line), i.e. banks holding fewer deposits. High-deposit and low-deposit ratios identify those banks that prior to the introduction of NIRP (2013) had a ratio of deposits to total assets above and below the median, respectively.

the summary statistics for our dependent variables. It clearly shows that high-deposit banks (i.e. the treatment group), as compared to low-deposit banks (i.e. the control group) appear to have improved their cost efficiency in the years after the introduction of NIRP. In particular, the related average score moves from 0.65 in 2011-2014 to 0.66 in 2015-2018, while the same figure for the control group declines from 0.69 to 0.68. Both groups experienced an increase in the cost-to-income ratio after the introduction of NIRP. However, while the increase for the control group is 2.95 percentage points (from 65.11% to 68.07%), the same figure for the treatment group is more modest, i.e. 1.48 percentage points (from 69.65% to 71.15%).

Panels B and E of Table 1 report the summary statistics for the bank balance sheet information. We consider the ratio of gross loans to total assets (LOANS) to measure the loan intensity of banks' balance sheets (Williams, 2012). On the one hand, given that loan production is relatively more costly than holding other assets (e.g. securities), due to costs associated with effective screening and monitoring, it is reasonable to expect an inverse relationship between bank asset structure and efficiency. On the other hand, banks with a greater share of loans in their balance sheets may face additional management pressure to deal with credit risk, hence improving bank efficiency. Bank size (SIZE) is computed as the natural logarithm of the bank total assets. The relationship between bank size and efficiency is not straightforward. Some studies (Berger et al., 1993; Miller and Noulas, 1996) document a positive relationship between

Table 1
Descriptive statistics for control and treatment groups before and after NIRP.

	Treatment (High-deposit banks - deposit-to-total assets ratio >= 67.61%)											
	Pre-NIRP (2011-2014)						NIRP period (2015-2018)					
	Obs	Avg	Std.	p25	Med	p75	Obs	Avg	Std.	p25	Med	p75
Panel A : Dependent variables												
Costeff (Score)	1498	0.65	0.12	0.61	0.67	0.72	1639	0.66	0.12	0.62	0.69	0.73
Cost-to-income (%)	1459	69.7	11.1	63.5	69.2	75.7	1602	71.1	11	64.9	70.7	76.8
Panel B : Bank specific characteristics												
LOANS (%)	1496	55.99	16.1	46.84	57.63	66.94	1638	58.22	15.48	49.11	60.63	69.37
SIZE (log)	1498	6.37	1.71	5.03	6.24	7.62	1639	6.53	1.66	5.21	6.43	7.68
ROA (%)	1475	0.39	0.46	0.19	0.33	0.53	1639	0.37	0.38	0.16	0.28	0.52
TOTCAP (%)	1399	18.37	7.13	14.15	17.47	21.12	1561	19.89	7.03	15.81	18.2	22.21
INT_OP (%)	1498	102.17	22.93	89.32	102.2	114.24	1639	81.76	17.91	72.2	80.81	89.79
LLP (%)	1477	8.99	22.95	1.47	6.32	14.45	1632	7.71	15.29	1.37	4.98	11.03
DEP_TA (%)	1498	79.97	5.44	76.37	80.12	83.69	1639	81.13	5.57	78.08	81.6	84.98
Loan_GR (%)	1183	4	12.2	1.3	3.8	6.7	1638	5.6	12.7	2.1	4.9	8
Zscore (score)	1475	1.248	0.437	1.052	1.281	1.518	1639	1.333	0.389	1.182	1.361	1.564
Panel C : Macroeconomic variables												
INFLATION (%)	1498	1.73	0.53	1.5	1.86	1.97	1639	1.42	0.46	1.13	1.51	1.7
GDP_g (%)	1498	1.16	1.45	0.42	0.66	2.23	1639	2.06	0.86	1.53	2.08	2.47
	Control (Low-deposit banks - deposit-to-total assets ratio < 67.61%)											
	Pre-NIRP (2011-2014)						NIRP period (2015-2018)					
Panel D : Dependent variables												
Costeff (Score)	2676	0.69	0.12	0.65	0.71	0.77	2800	0.69	0.13	0.63	0.71	0.77
Cost-to-income (%)	2440	65.1	15.3	56.9	64.8	72.2	2620	68.1	15	59.9	67.8	74.8
Panel E : Bank specific characteristics												
LOANS (%)	2672	62.22	18.03	53.01	65.14	75.48	2799	63.61	16.8	54.86	66.62	75.95
SIZE (log)	2676	7.64	2.27	5.92	7.36	9.25	2800	7.73	2.18	6.08	7.46	9.22
ROA (%)	2551	0.38	0.68	0.17	0.32	0.58	2800	0.4	0.58	0.17	0.33	0.57
TOTCAP (%)	2458	18.04	9.05	13.39	15.66	19.42	2635	19.56	8.61	15	17.06	20.93
INT_OP (%)	2676	110.03	28.17	93.01	109.1	128.39	2800	88.02	24.68	72.74	84.76	98.56
LLP (%)	2608	27.58	34.84	7.38	17.77	37.93	2771	22.12	29.47	4.76	12.74	30.38
DEP_TA (%)	2676	51.68	16.35	41.55	53.69	65.18	2800	59.36	16.05	51.7	63.15	71.09
Loan_GR (%)	2068	1.8	17.3	−2.3	1.5	5.5	2799	2.9	76.3	0.5	4.2	8.4
Zscore (score)	2552	1.262	0.58	1.003	1.281	1.612	2800	1.321	0.514	1.066	1.331	1.627
Panel F : Macroeconomic variables												
INFLATION (%)	2676	1.33	0.67	0.91	1.45	1.61	2800	1.09	0.55	0.9	1.05	1.18
GDP_g (%)	2676	0.11	1.9	−1.03	0.42	0.74	2800	1.75	1.43	1.1	1.67	2.23

Notes: The table presents summary statistics for the variables employed in the analysis. The table is divided in six panels: Panels A, B and C report the statistics for the dependent, bank-specific and macroeconomic variables for the control group prior and after the introduction of NIRP in June 2014. Panels D, E and C report the statistics for the dependent, bank-specific and macroeconomic variables for the treated group prior and after the introduction of NIRP. Control group banks are those that have a deposit-to-total assets ratio in 2013 below the median (67.61%), while banks in the treated group have a deposit-to-total assets ratio in 2013 above the median (67.61%). Costeff is the estimated cost efficiency score. Cost-to-income is the ratio of operating expenses to operating income. LOANS is the ratio of gross loans-to-total assets. SIZE is the logarithm of the bank total assets. ROA is the ratio of net income-to-total assets. TOTCAP is the total capital ratio. INT_OP is the ratio of interest income-to-operating income. LLP is the ratio of loan loss provisions-to-net interest income. DEP_TA is the ratio total deposits divided by total assets. Loan_GR is the annual growth rate of loans. Zscore is the ROA plus the ratio of equity over total assets divided by the standard deviation of the ROA at the country level. INFLATION is the growth rate of the Consumer Price Index (CPI). GDP_g is the annual growth in gross domestic product (GDP).

the two variables, while other authors (DeYoung and Nolle, 1996; Girardone et al. 2004) find an inverse association. Other studies do not observe any significant efficiency advantage for large banks (Berger and Mester, 1997; Pi and Timme, 1993). Bank profitability is captured by the ratio of net income to total assets (ROA). More profitable banks usually tend to be more efficient (Casu and Girardone, 2004). We account for the level of bank capitalization, by using the total regulatory capital ratio (TOTCAP). We predict a positive relationship between the level of the capital ratio and our variables of interest as a higher capitalization mitigates agency problems between managers and shareholders, thereby improving bank efficiency (Mester, 1996). We include a measure of income stream (INT_OP), defined as the ratio of interest income to operating income, to control for banks' business models. Roengpitya et al. (2017) find that banks with a more retail-oriented business model exhibit lower cost-to-income ratios in comparison to banks that generate most of their revenues from trading activities. Finally, we introduce a measure of bank credit risk, calculated as the ratio of loan loss provisions to net interest income (LLP). Fiordelisi et al. (2011) show that cost efficiency declines as credit risk increases.

As country-level controls (Panels C and F of Table 1), we employ (i) the inflation rate (INFLATION); and (ii) the growth of gross domestic product (GDP_g). According to Barth et al. (2013) a country's inflation is inversely linked to bank efficiency, suggesting that a

lower inflationary environment is associated with more efficient bank operations. Moreover, Fries and Taci (2005) document that costs may decrease with overall economic growth because of corresponding improvements in the quality of public institutions.[18]

5. Empirical Results

5.1. Baseline results

Table 2 presents the results of the baseline analysis performed to test our first hypothesis on bank cost efficiency. The dependent variable is the estimated bank cost efficiency score, ranging between 0, which indicates an entity with structural inefficiency, and 1 which identifies the theoretical best practice frontier. In order to capture the effect of NIRP on bank cost efficiency, we control for a number of relevant bank-level factors, commonly used in banking studies, as well as for two macroeconomic variables. Specifically, the first column of Table 2 shows the impact of the introduction of NIRP in 2014 (our intervention) on the treated group (high- deposit banks) as compared to the untreated group (low-deposit banks) without the inclusion of bank- and country-specific controls. In the second and third columns of Table 2, we progressively introduce bank-specific control variables (column 2) and macroeconomic controls (column 3). All regressions include bank and year fixed effects. Robust standard errors are clustered at the bank-level.

The coefficient on (*High-deposits*Post*) is positive and statistically significant at the 1% level in all specifications. This suggests that the move of policy rates into negative territory has pushed high-deposit banks, which are more materially affected by the NIRP, to substantially enhance their cost structure compared to low-deposit banks, most likely to offset the potential contraction on the profit side. The corresponding coefficient is also economically meaningful. Specifically, high-deposit banks improve their cost efficiency by about 0.0162 points after NIRP in comparison to low-deposit banks. We assert that profitability pressure may force high-deposit banks to consolidate and strengthen their operational (cost) efficiency. Indeed, Jobst and Lin (2016) argue that "pressure on profitability [. . .] may explain why some banks have already announced significant cuts in operating costs (closing of branches and reduction in staffing)." Also, other studies (Scheiber et al., 2016 and Madaschi and Pables Nuevo, 2017) assessing the development in the cost to income ratio in the immediate pre- and post- NIRP periods, confirm improvements in bank cost expenses. This result is particularly important for policymakers as it indicates that negative interest rates can orientate banks' incentives towards strategies intended to improve their performance.

In Fig. 4, we also plot the time-varying coefficients (based on column 1 of Table 2) on the treatment prior to and after NIRP to investigate in detail the dynamics of the effect. From a policymaker perspective, it is relevant to appreciate if high-deposit banks enhanced their cost efficiency immediately after the introduction of NIRP or whether this response was delayed. In addition, the dynamic DiD informs on the suitability of the DiD econometric identification strategy. We do not find statistically significant differences between the treatment and the control group prior to the introduction of NIRP as the two confidence intervals largely overlap suggesting that the parallel trend assumption holds and the DiD framework is valid. However, after the introduction of NIRP, high-deposit banks improved progressively their cost efficiency (the only exception being the slight decline recorded in 2018) in comparison to low-deposit banks, which after NIRP showcased a downward trend. Small but steady improvements in cost efficiencies as a reaction to the negative interest rate environment are reasonable as they require strategic reconfiguration of processes, branches, employees and technologies.

Results hold up well when we add bank-specific variables and macroeconomic factors (columns 2 and 3 of Table 2, respectively). The coefficient on the NIRP-effect retains its sign and significance, suggesting robustness in our inference. Several bank-level characteristics are also significantly related to cost efficiency. Specifically, bank size, lending growth and the Z-score appear to be positively related to cost efficiency. The coefficient on the variable SIZE is positive and statistically significant at the 5% level in both model specifications (columns 2 and 3), suggesting that larger banks are better equipped for improvements on the costs' side, benefiting from efficiency gains (Berger et al., 1993; Miller and Noulas, 1996; Barth et al. 2013). Loan_GR displays a positive and statistically significant (at the 5% level in both model specifications) relationship with cost efficiency. Higher loan growth may reduce the production costs at the margin improving cost efficiency. Most importantly, controlling for loan growth allows us to rule out differences in the lending behaviour between high- and low-deposit banks, hence controlling for the possibility that high-deposit banks expand their loan portfolios more than low-deposit banks in response to negative interest rates (Brown, 2020). The Z-score is also positively correlated to cost efficiency, presenting a statistical significance between 1% in column 2 and 5% in column 3. According to DeYoung et al. (1995), less risky banks are more efficient as stock- holders and managers are more directly involved in bank policy. In addition, the inclusion of the Z-score variable allows us to control for the possibility that high-deposit banks may have assumed more risk, relative to low-deposit banks, following the introduction of NIRP. Turning to the macroeconomic controls, we find an inverse and highly statistically significant relationship between GDP growth and our variable of interest.[19]

[18] Table C in Appendix A provides a detailed definition of the variables and the associated sources.

[19] In Table D in Appendix A, we follow the approach used by Gomez et al. (2021) and interact the lagged bank- specific characteristics with the *Post* dummy, thus allowing for the possibility that these control variables have a heterogeneous impact on bank cost efficiency following the introduction of NIRP. The results show that some of the interaction terms, most notably the level of capitalisation (TOTCAP), the interest income to operating income ratio (INT_OP) and the loan loss provision to net interest income ratio (LLP) are statistically significant indicating that banks with lower level of provisioning, less capital and that have a business model more reliant on interest income improved their cost efficiency after the introduction of NIRP. Our coefficient of interest (i.e. High-deposits*Post) holds up well also when we allow NIRP to have an effect on the bank-specific characteristics that can drive a change in the cost efficiency.

Table 2
Baseline results.
This table shows the results of the baseline specification performed on the bank-level panel dataset. *Costeff* is the estimated cost efficiency score. *High−deposits* is a dummy variable that takes the value 1 if in 2013 (i.e. before NIRP), the average ratio of deposits to total assets of bank i located in a NIRP- affected country j was above the median, and 0 otherwise. *Post* is a dummy variable that assumes the value 1 after the introduction of NIRP, and 0 otherwise. LOANS is the ratio of gross loans to total assets. SIZE is the logarithm of bank total assets. ROA is the ratio of net income to total assets. TOTCAP is the total capital ratio. INT_OP is the ratio of interest income to operating income. LLP is the ratio of loan loss provisions to net interest income. Loan_GR is y-o-y gross loan growth. Zscore is the (ROA plus E/TA)-to-standard deviation of ROA at the country level. INFLATION is the growth rate of the Consumer Price Index (CPI). GDP_g is the annual growth in gross domestic product (GDP). Robust standard errors are clustered at bank-level. *, **, *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

VARIABLES	(1) costeff	(2) costeff	(3) costeff
High-deposits*Post	0.0184***	0.0149***	0.0115***
	(0.0041)	(0.0038)	(0.0040)
L.LOANS		0.0004	0.0003
		(0.0003)	(0.0003)
L.SIZE		0.0472***	0.0458***
		(0.0164)	(0.0163)
L.ROA		−0.0057	−0.0038
		(0.0035)	(0.0034)
L.TOTCAP		0.0004	0.0004
		(0.0005)	(0.0005)
L.INT_OP		−0.0128	−0.0121
		(0.0165)	(0.0168)
L.LLP		0.0000	0.0000
		(0.0001)	(0.0001)
L.Zscore		0.0422***	0.0405***
		(0.0135)	(0.0134)
Loan_GR		0.0090**	0.0089**
		(0.0036)	(0.0036)
L.INFLATION			0.0015
			(0.0021)
L.GDP_g			−0.0037***
			(0.0010)
Observations	8455	6760	6760
R-squared	0.0146	0.0600	0.0659
Number of banks	1107	1053	1053
Bank Fe	Yes	Yes	Yes
Time Fe	Yes	Yes	Yes
Cluster	Bank	Bank	Bank

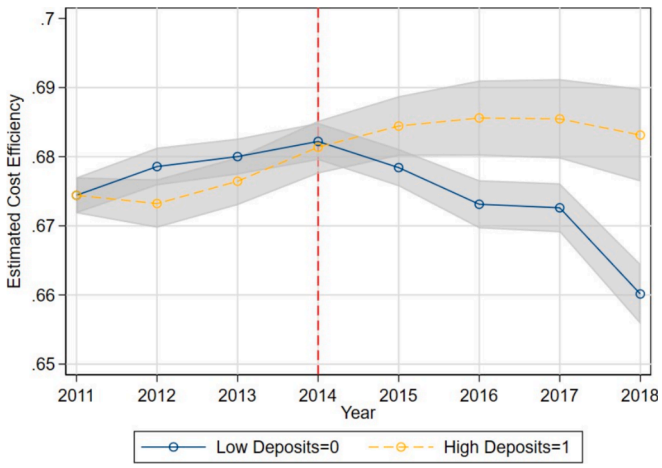

Fig. 4. Difference-in-differences dynamic coefficients plot.
This figure plots the dynamic coefficients of the DiD estimation over the sample period. The solid blue line represents the estimated DiD coefficients for the control group (i.e. low-deposit banks) whilst the yellow dashed line the estimated DiD coefficients for the treatment group (i.e. high-deposit banks). Low deposits are those banks with an above-median level of deposits to total assets, and vice versa for high deposit banks. The vertical dashed red line indicates the implementation of NIRP. The shaded grey areas indicate a 90% confidence interval.

5.2. NIRP and cost efficiency: the role of bank-specific characteristics and market competition

In this section, we deepen our understanding of the relationship between NIRP and cost efficiency by analysing whether the heterogeneity in bank-specific characteristics matters for the banks' response to negative interest rates. Specifically, in order to test our second hypothesis, we perform a set of additional regressions where we account for banks' balance sheet and market conditions in place prior to the introduction of NIRP.

First, we aim to appreciate whether NIRP has a stronger effect on the cost efficiency of high- deposit banks depending on their size. Smaller banks engaging in relationship lending incur higher monitoring costs, given that the "soft" information is gathered and updated through costly long-term lending relationships (Petersen and Rajan, 1994; Uchida et al., 2012; Bolton et al. 2016). Consequently, for smaller retail-oriented banks may be more difficult to react to NIRP by improving costs via closing up branches, for instance. In addition, large banks due to greater international reach, potential to expand lending abroad and more diversified portfolios are better equipped to mitigate the detrimental effects of NIRP on margins and profits (Molyneux et al., 2019). They can effectively exploit interest rate cuts and generate gains on held-for-trading fixed income securities, as well as raise fees and commissions income more easily than smaller banks (Molyneux et al., 2021). We should, therefore, expect greater improvements in cost efficiencies for

Table 3
NIRP and cost efficiency: the role of bank-specific characteristics and market competition.
This table shows the results of the triple interaction regressions performed on the bank-level panel dataset. For a definition of the variables included in the econometric specification refer to Table C in Appendix A. *, **, *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

VARIABLES	(1) costeff	(2) costeff	(3) costeff	(4) costeff	(5) costeff
High-deposits*Post	0.0219***	0.0028	0.0187***	−0.0088	−0.0016
	(0.0048)	(0.0051)	(0.007)	(0.0059)	(0.0062)
Post*Quartile_Size	0.0048				
	(0.0066)				
High-deposits*Post*Quartile_Size	−0.0286***				
	(0.009)				
L.LOANS	0.0001	0.0003	0.0004	0.0004	
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	
L.SIZE		0.0434***	0.0457***	0.0438***	0.0362**
		(0.0161)	(0.0160)	(0.0164)	(0.0156)
L.ROA	−0.0008		−0.0033	−0.0018	−0.0036
	(0.0039)		(0.0033)	(0.0034)	(0.0035)
L.TOTCAP	0.0004	0.0004	0.0002	0.0007	0.0004
	(0.0005)	(0.0005)	(0.0005)	(0.0005)	(0.0004)
L.INT_OP	−0.0117	−0.0119	−0.02	−0.0121	−0.0121
	(0.0172)	(0.0166)	(0.0158)	(0.0168)	(0.0167)
L.LLP	−0.0000	0.0000		−0.0000	0.0000
	(0.0001)	(0.0001)		(0.0001)	(0.0001)
Loan_GR	0.0086***	0.0088**	0.0011	0.0090**	
	(0.0033)	(0.0036)	(0.0020)	(0.0036)	
L.Zscore	0.018	0.0363***	0.0303**	0.0330**	0.0367***
	(0.0170)	(0.0135)	(0.0128)	(0.0137)	(0.0130)
L.INFLATION	0.0012	0.0017	0.0017	0.002	0.0011
	−0.0022	−0.0021	−0.002	−0.0021	−0.0021
L.GDP_g	−0.0043***	−0.0037***	−0.0031***	−0.0041***	−0.0033***
	(0.0011)	(0.0011)	(0.0010)	(0.0011)	(0.0010)
Post*Quartile_ROA		−0.0100**			
		(0.0048)			
High−deposits*Post*Quartile_ROA		0.0171**			
		(0.0078)			
Post*Quartile_LLP			0.0224***		
			(0.0049)		
High−deposits*Post*Quartile_LLP			−0.0172**		
			(0.0084)		
Post*Quartile Lerner				0.0022	
				(0.0055)	
High-deposits*Post*Quartile_Lerner				0.0352***	
				(0.0077)	
Post*Quartile Loan_g					−0.0278***
					(0.0056)
High-deposits*Post*Quartile_Loan_g					0.0152*
					(0.0079)
Observations	6760	6760	7031	6760	6762
R-squared	0.0522	0.0677	0.0624	0.0812	0.0677
Number of id	1053	1053	1059	1053	1053
Bank Fe	Yes	Yes	Yes	Yes	Yes
Time Fe	Yes	Yes	Yes	Yes	Yes
Cluster	Bank	Bank	Bank	Bank	Bank

large, high-deposit banks. To test this hypothesis, we triple-interact our treatment dummy (*High-deposits*Post*) with a dummy variable labelled *Quartile_Size* which is equal to 1 if a bank prior to NIRP (2013) has total assets below the first quartile of the bank's total asset distribution, and 0 otherwise. The results are displayed in column 1 of Table 3 and are interesting for two main reasons. First, the coefficient on the interaction term *High-deposits*Post* is positive and statistically significant at the 1% level, indicating that post-NIRP improvements in cost efficiencies for high-deposit banks are driven by larger banks. Second, the coefficient on the triple interaction *High-deposits*Post*Quartile_Size* is negative and statistically significant at the 1% level, suggesting that smaller high-deposit banks appear to have a lower capacity for manoeuvre to enhance their cost efficiency.

Second, we investigate whether high-deposit banks that are less profitable face additional pressure to improve their cost efficiency in comparison to more profitable institutions. Indeed, high-deposit, less profitable banks are left with fewer options to tackle negative interest rates. First, low profitability impairs capital accumulation via retained earnings and, consequently, the ability of banks to increase lending volumes (Molyneux et al. 2020). In addition, less profitable banks tend to avoid *"gambling for resurrection"* by increasing risk-taking behaviour to boost profitability under negative rates as the latter are implemented by policymakers in periods of below-target inflation and, thus, economic uncertainty and lack of economic growth (Bongiovanni et al., 2021). Therefore, we expect a stronger reaction to NIRP in terms of cost enhancements stemming from less profitable banks. To test this hypothesis, we triple-interact our treatment dummy (*High-deposits*Post*) with a dummy variable labelled *Quartile_ROA* which takes the value 1 if a bank prior to NIRP has a ROA below the first quartile of the corresponding distribution, and 0 otherwise. The results are reported in column 2 of Table 3. In line with our expectations, the coefficient on the triple interaction term (*High-deposits*Post*Quartile_ROA*) is positive and highly statistically significant, reflecting a more pronounced reaction to NIRP of less profitable banks.

Third, we explore whether enhancements in cost efficiency following the implementation of NIRP depend on bank asset quality. Indeed, banks with deteriorated asset quality may face additional impediments to react to NIRP for several reasons. On the one hand, lower asset quality reduces bank profitability, thus limiting banks' ability to expand lending volumes. On the other hand, banks carrying sizeable amounts of *legacy assets* cannot exploit in full the beneficial implications of negative interest rates on bank funding costs as investors expect a higher premium for lending to institutions with impaired asset quality. Based on these considerations, we predict greater improvements in cost efficiency for those high-deposit banks with riskier loan portfolios. For this exercise, we triple-interact our treatment dummy (*High-deposits*Post*) with a dummy variable labelled *Quartile_LLP* which takes the value 1 if a bank prior to NIRP (2013) has a LLP ratio below the first quartile of the related distribution, and 0 otherwise. The results are reported in column 3 of Table 3. The coefficient on the double interaction *High-deposits*Post* is positive and highly statistically significant, confirming our hypothesis that banks with deteriorated asset quality (i.e. those banks with greater provisioning) improve their cost efficiency after NIRP. In contrast, the coefficient on the triple interaction *High-deposits* Post*Quartile_LLP* is negative and statistically significant at the 1% level, suggesting that banks with lower levels of provisioning did not face the same urgency, given that a better asset quality helps to sustain profits, also when policy interest rates are negative.

Fourth, we look at whether banks with weaker lending growth before NIRP have stronger incentives to improve their cost efficiency in response to NIRP because of the limited capacity to further boost lending volumes in a negative interest rate environment. For this test, we triple-interact our treatment dummy (*High-deposits*Post*) with a dummy variable labelled *Quartile_Loan_g* which is equal to 1 if a bank prior to NIRP (2013) has a lending growth below the first quartile of the lending growth distribution, and 0 otherwise. The results are reported in column 5 of Table 3. The coefficient on the triple interaction term *High-deposits*Post*Quartile_Loan_g* is positive and statistically significant at the 10% level, reflecting the difficulty of banks with an already limited lending growth prior to NIRP to counter off the detrimental effects of NIRP on margins and profits. Consequently, these banks appear to react to NIRP by improving their cost efficiency.

Lastly, we assess the impact of NIRP on bank cost efficiency in the context of competitive banking sectors. For this exercise, we use the Lerner index at the country level as a proxy for competitive conditions.[20] Sørensen and Werner (2006) argue that banks operating in less competitive environments undertake slower adjustments to interest rates, which slows the transmission of monetary policy (Avignone et al., 2021) and contributes to sustaining banks' net interest margins. In addition, Adabi et al. (2023) present a "reversal interest rate" hypothesis, according to which there is a rate of interest at which an accommodative monetary policy "reverses" its effect and becomes contractionary. They show that a low interest rate policy is likely to have a more limited effect on bank lending in competitive markets because of the associated pressure on net interest margins. Consequently, we argue that banks operating in less competitive banking sectors may not have the same incentives to improve their cost efficiency, compared to banks operating in more competitive markets, due to the weaker adverse effects of negative rates on margins. To test for this possibility, we triple-interact our treatment dummy (*High−deposits*Post*) with a dummy variable labelled *Quartile_Lerner* which takes the value 1 if a bank prior to NIRP (2013) operates in a market with a Lerner index below the first quartile of the corresponding distribution, and 0 otherwise. The results reported in column 4 of Table 3 largely support our intuition. Indeed, the coefficient on the triple interaction term *High−deposits*Post*Quartile_Lerner* is positive, statistically significant (at the 1% level) and sizeable in magnitude, confirming that banks operating in more competitive banking sectors face additional pressure to improve their cost efficiency likely because of the stronger compression on the net interest margins under NIRP.

[20] Alternatively, we also use the Boone index and a measure of banking market concentration (i.e. the Herfindahl- Hirschman Index). The results, unreported but available upon request, are consistent with those obtained by using the Lerner index.

6. Robustness Checks

6.1. Single frontier approach

Although the two-step SFA has been widely employed in the empirical banking literature (see, amongst others, Allen and Rai, 1996; Berger and DeYoung, 1997; Berger and Mester, 1997; Bos and Kolari, 2005; Lin and Zhang, 2009), the efficiency analysis literature has raised some concerns about the two-step estimation procedures (Battese and Coelli, 1995; Huang and Liu, 1994; Huang and Wang, 2002; Wang and Schmidt, 2002; Mohanty et al., 2013). A first problem arises from the observation that the two-step approach does not account for heteroskedasticity in the inefficiency component of the error term. In addition, misspecifications occur if correlations between input prices and bank characteristics exist. In particular, Wang and Schmidt (2002) argue that the estimates from the second step tend to be downward biased if input prices are correlated with bank-specific characteristics.

We delve into this possibility by performing a single-step estimation approach. Table 4 show the results of our baseline regression obtained by using the one-stage approach. The findings are overall in line with those obtained by using the two-step approach.

6.2. Placebo test and the ZLB

When using a DiD estimation approach it is fundamental to remove the possibility that the identified behaviour of the variable of interest, in our case the efficiency scores, might have already manifested prior to the shock. In practice, we need to ensure that bank cost efficiency for the treatment group had not already diverged prior to the adoption of NIRP in comparison to the control group - for instance, as a result of the anticipation of the adverse effects of NIRP, or for some non-identified bank-specific reasons. This would invalidate our empirical strategy and, therefore, the choice of the DiD estimation. To deal with this aspect, a *placebo* exercise can be set up, based on which the data is tricked so that the considered shock occurs at an earlier date, compared to the real one. If the estimated coefficient on the "false" NIRP-adoption-date lacks statistical significance, we can reasonably infer that our baseline coefficient is effectively capturing a genuine shock (the introduction of NIRP, in our case).

In addition, a *placebo* test informs on the differences between interest rates at the ZLB (or above) and negative interest rates. Indeed, statistically significant differences in bank cost efficiency between the treatment and the control group prior to NIRP would suggest, *ceteris paribus*, enhancements in cost efficiency for high-deposit banks also in positive interest rates territory.

In Table 5, we report the results from the estimation in which we limit our time dimension to the pre-NIRP period (2011-14) and set a "false" introduction of NIRP in 2013.[21] The interaction coefficient (*High−deposits*"*false*"*Post*) retains its positive sign, but it is smaller in magnitude and lacks statistical significance, thereby adding further robustness to the validity of our baseline estimation. Moreover, this evidence informs on the pass-through of interest rates on bank cost efficiency. Low, but still positive interest rates are shown not to be effective in pushing banks to enhance cost efficiency. This seems to confirm the hypothesis advanced in other studies (Eggertsson and Woodford, 2003; Heider et al., 2019) according to which, by squeezing the net interest margins and the profitability due to the stickiness of retail deposits, the adoption of NIRP appears to drive banks to engage in different off-setting strategies. Specifically, in our paper, we identify a proactive behaviour towards the enhancement of bank cost efficiency.

6.3. Alternative definition of the treatment variable

In the baseline specification, we defined as *treated* those banks with a deposit-to-total assets ratio above the median value pre-NIRP (2013). In this section, we provide a variation to the baseline specification by redefining the treatment dummy in two additional ways. First, rather than focusing on the median value, we consider as treated those banks with a pre-NIRP (2013) deposit-to-total assets ratio above the top-tercile of the related distribution, while the control group considers the bottom-tercile deposit ratio. Second, we replace our treatment dummy variable with the lagged value of the deposit-to-total assets ratio, expressed as a continuous variable, that captures the intensity of the treatment effect. Using a continuous variable, rather than a dummy indicator, has the potential to allow for a more accurate estimation of the intensity of the effect (when employing a dummy variable entities are grouped based on a specified thresh- old). However, in our empirical settings, the dummy variable retains the advantage of allowing for non-linearity in the estimation of NIRP on bank cost efficiency. The use of both approaches, therefore, further validates our findings.

Evidence reported in Table 6 (columns 1 to 6) suggests that our results are overall robust to a different definition of the treatment variable. The definition of the treatment variable based on the tercile of the deposit to asset ratio distribution produces results qualitatively consistent with those discussed for the baseline specification. In addition, we document a positive and highly statistically significant coefficient on the continuous variable, suggesting that the higher the deposit-to-total assets ratio the larger the improvements achieved in terms of cost efficiency, post NIRP. As a graphical illustration of this relationship, we plot in Fig. 5 the estimated coefficients of *Costeff* at different levels of the deposit-to-total assets ratio (the employed coefficients are from the estimation performed in column 4 of Table 6). We find that, at around 60% of the deposit-to-total assets ratio, banks increased their cost efficiency in comparison to the pre-NIRP period, further corroborating the core hypothesis of this study based on which high-deposit euro area

[21] In an unreported test, we perform an additional DiD estimation limiting the time dimension to 2011-2013 and setting the "false" introduction of NIRP in 2012. The results are consistent with those discussed in this section and available upon request.

Table 4
Cost efficiency frontier estimation: one-stage approach.
This table shows the stochastic cost frontier models. It provides estimators for the parameters of a linear model with a disturbance that is assumed to be a mixture of two components, which have a strictly non-negative and symmetric distribution, respectively. The frontier can fit models in which the non-negative distribution component (a measurement of inefficiency) is assumed to be from a half-normal distribution. Loans and other earning assets are the outputs, Q1 and Q2 respectively. Z-score is a measure of banks' riskiness. It is the sum of ROA plus the ratio of equity-to-total assets, all divided by the standard deviation of ROA at the country level. P1 is the cost of borrowed funds (W1) divided by the cost of labour (W3). P2 is the cost of physical capital (W2) divided by the cost of labour (W3). EQUITY (EQ) is the bank equity. TIME (T) is a time trend. High-deposits is a dummy variable that takes the value 1 if in 2013 (i.e. before NIRP), the average ratio of deposits to total assets of bank i located in a NIRP-affected country j was above the median, and 0 otherwise. Post is a dummy variable that assumes the value 1 after the introduction of NIRP, and 0 otherwise. All inputs and outputs are in logarithmic form. *, **, *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

VARIABLES	(1) Frontier
Q1	0.4956***
Q2	0.4193***
Z-score	0.0186
P1	0.4482***
P2	0.4628***
EQUITY	-0.04
1/2 P1P1	-0.0096***
1/2 P1P2	-0.0120*
1/2 P2P2	-0.0646***
P1Q1	0.0110***
P2Q1	-0.0670***
P1Q2	-0.0182***
P2Q2	0.0064
EQQ1	-0.0059
EQQ2	-0.0231***
EQP1	-0.0187***
EQP2	0.0411***
1/2 Q1Q1	0.1160***
1/2 Q1Q2	-0.1366***
1/2 Q2Q2	0.0575***
1/2 EQUITY^2	0.0373***
TIME	0.0174
1/2 TIME^2	-0.0031
TQ1	-0.0038
TQ2	-0.0043*
TW1	-0.0161***
TW2	-0.0002
Determinant of efficiency (ln)	
High-deposits*Post	0.0662*
Observations	8,451
Number of banks	1,107

banks reacted to the negative interest rate environment by improving their cost efficiency.[22]

6.4. *Accounting-based measure: Cost-to-income ratio*

As a final robustness check, we replace our original dependent variable (i.e. cost efficiency scores estimated through the SFA method), with an accounting-based measure. For this exercise, we employ the cost-to-income ratio, a typical measure of banks' efficiency and productivity, calculated as the ratio of operating expenses to operating income.

Table 7 reports the related results. The interaction coefficients (*High−deposits*Post*) are negative and overall statistically significant at the 1% level (except for the univariate model in column 1), indicating that high-deposit banks managed to lower their cost-to-income ratio after the introduction of NIRP, compared to banks in the control group. Specifically, high-deposit banks reduced their cost-to-income ratio by 2.18-2.57% – depending on the econometric specification – following the intervention, with respect to the group of low-deposit banks. This evidence adds further robustness to our baseline findings and appears to be in line with the existing literature (Scheiber et al., 2016; Madaschi and Pables Nuevo, 2017) that documents improvements in bank cost expenses in the immediate pre- and post-NIRP periods.

7. Conclusions

This paper investigates the impact of NIRP on euro banks' cost efficiency. To the best of our knowledge, we are the first to consider

[22] In Table E in Appendix A, we further strengthen the continuous variable approach by using the deposit-to-total assets ratio as of 2013 and keeping it fixed throughout the sample period. The results are consistent with those obtained when using the lagged deposit-to-total assets ratio.

Table 5
Placebo test.
This table shows the results of the placebo test performed on the bank-level panel dataset. The "false" introduction of NIRP is set in 2013. *Costeff* is the estimated cost efficiency score. LOANS is the ratio of gross loans to total assets. SIZE is the logarithm of bank total assets. ROA is the ratio of net income to total assets. TOTCAP is the total capital ratio. INT_OP is the ratio of interest income to operating income. LLP is the ratio of loan loss provisions to net interest income. Loan_GR is y-o-y gross loan growth. Zscore is the (ROA plus E/TA)-to-standard deviation of ROA at the country level. INFLATION is the growth rate of the Consumer Price Index (CPI). GDP_g is the annual growth in gross domestic product (GDP). Robust standard errors are clustered at the bank-level. *, **, *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

VARIABLES	(1) costeff	(2) costeff	(3) costeff
High-deposits* "false"Post	0.0036	-0.0003	-0.0002
	(0.0025)	(0.0035)	(0.0036)
L.LOANS		0.0012***	0.0011***
		(0.0003)	(0.0004)
L.SIZE		0.0439***	0.0381**
		(0.0168)	(0.0166)
L.ROA		-0.0049	-0.0024
		(0.0049)	(0.0042)
L.TOTCAP		0.0006	0.0006
		(0.0005)	(0.0005)
L.INT_OP		-0.0037	0.0007
		(0.014)	(0.0148)
L.LLP		0.0000	-0.0000
		(0.0001)	(0.0001)
L.Zscore		0.0200	0.0147
		(0.0123)	(0.0111)
LOAN_GR		0.0428***	0.0412***
		(0.0117)	(0.0115)
L.INFLATION			0.0038
			(0.0026)
L.GDP_g			-0.0035*
			(0.0019)
Observations	4033	2622	2622
R-squared	0.0071	0.0505	0.0645
Number of id	1107	1031	1031
Bank Fe	Yes	Yes	Yes
Time Fe	Yes	Yes	Yes
Cluster	Bank	Bank	Bank

this unexplored channel and test whether banks responded to negative policy rates by enhancing efficiency with respect to costs. Existing studies (Arce et al., 2023; Bottero et al., 2022; Heider et al., 2019; Bubeck et al., 2020; Bongiovanni et al., 2021; Demiralp et al., 2021; amongst others) focused on other levers that banks exploited, since mid-2014, to tackle the detrimental effects of NIRP on interest margins and profitability. We fill the gap in the literature and provide empirical evidence of the way banks *made a virtue out of necessity* reacting to the unprecedented introduction of negative interest rates in the euro area.

Our identification strategy relies on the use of standard SFA, to estimate cost score efficiencies, and a robust DiD setting, which enables us to compare the cost efficiency-related behavior of banks with a different deposit to assets ratios (namely, high-deposit and low-deposit banks), prior and after the adoption of NIRP. We also account for a comprehensive set of bank-specific characteristics, as well as two macroeconomic factors. Our analysis is based on a sample of 1,130 banks from 17 euro area countries for the period 2011-2018.

Our findings overall suggest that treated banks reacted to NIRP by improving their cost efficiency. We provide evidence of greater incentives to improve cost efficiency stemming from larger and less profitable banks. Moreover, banks with an already constrained lending growth tend to enhance their cost efficiency following the implementation of the NIRP by the ECB. In addition, we find that asset quality issues affect the channel through which negative rates impact banks' efficiency, as institutions with better loan portfolios have not faced the same urgency to cut costs as their peers with weaker asset quality. On the other hand, banks operating in more competitive banking sectors are subject to additional pressure to improve their cost efficiency. Our results are robust to a number of additional tests, such as the use of "false" treatment dates, as well as alternative definitions of both the treatment and dependent variables.

In addition to the gains from building on existing empirical evidence on cost efficiency in the euro area banking sector, our findings advance the ongoing debate on the effectiveness and implications of NIRP. We believe our results to be, therefore, of primary interest to academics, policymakers and supervisors. Albeit outside the policy scope of the ECB, the enhanced cost efficiency of euro area banks in

Table 6
Results using alternative definitions of the treatment variable.
This table shows the results of the robustness check performed on the bank-level panel dataset. *Costeff* is the estimated cost efficiency score. LOANS is the ratio of gross loans to total assets. SIZE is the logarithm of bank total assets. ROA is the ratio of net income to total assets. TOTCAP is the total capital ratio. INT_OP is the ratio of interest income to operating income. LLP is the ratio of loan loss provisions to net interest income. INFLATION is the growth rate of the Consumer Price Index (CPI). Loan_GR is y-o-y gross loan growth. Zscore is the (ROA plus E/TA)-to-standard deviation of ROA at the country level. GDP_g is the annual growth in gross domestic product (GDP). Robust standard errors are clustered at the bank-level. *, **, *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

VARIABLES	(1) costeff	(2) costeff	(3) costeff	(4) costeff	(5) costeff	(6) costeff
High-deposits(tercile)*Post	0.0266***	0.0226***	0.0202***			
	(0.0045)	(0.0044)	(0.0047)			
L.LOANS		0.0002	0.0001		0.0005*	0.0004
		(0.0003)	(0.0004)		(0.0003)	(0.0003)
L.SIZE		0.0363**	0.0355*		0.0372**	0.0366**
		(0.0182)	(0.0182)		(0.0153)	(0.0152)
L.ROA		-0.004	-0.003		-0.0053	-0.0042
		(0.0039)	(0.0038)		(0.0038)	(0.0037)
L.TOTCAP		0.0005	0.0005		0.0003	0.0003
		(0.0005)	(0.0005)		(0.0004)	(0.0004)
L.INT_OP		-0.0162	-0.0162		-0.0126	-0.0124
		(0.0182)	(0.0184)		(0.0154)	(0.0155)
L.LLP		-0.0000	-0.0000		-0.0000	-0.0000
		(0.0001)	(0.0001)		(0.0001)	(0.0001)
L.Zscore		0.0304*	0.0296*		0.0291**	0.0284**
		(0.0159)	(0.0159)		(0.0132)	(0.0132)
Loan_GR		0.0085**	0.0084**		0.0082**	0.0082**
		(0.0034)	(0.0034)		(0.0034)	(0.0034)
L.INFLATION			0.0000			-0.0000
			(0.0024)			(0.0021)
L.GDP_g			-0.0022**			-0.0024**
			(0.0010)			(0.0010)
L.DEP_TA				-0.0015***	-0.0016***	-0.0015***
				(0.0002)	(0.0003)	(0.0003)
High-deposits*Post (cont. treatment)				0.0007***	0.0005***	0.0005***
				(0.0001)	(0.0001)	(0.0001)
Observations	6200	4987	4987	7659	6730	6730
R-squared	0.0407	0.087	0.0896	0.0488	0.087	0.0897
Number of id	807	775	775	1104	1052	1052
Bank Fe	Yes	Yes	Yes	Yes	Yes	Yes
Time Fe	Yes	Yes	Yes	Yes	Yes	Yes
Cluster	Bank	Bank	Bank	Bank	Bank	Bank

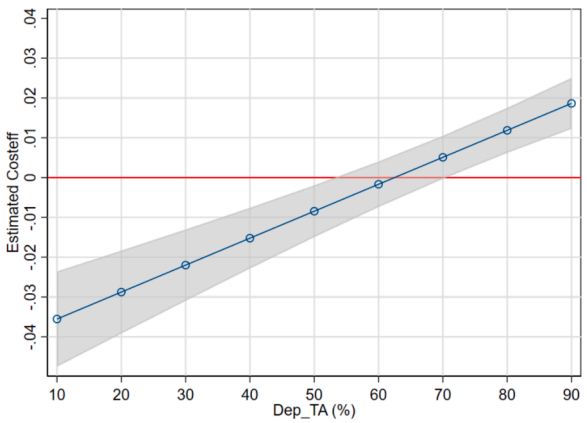

Fig. 5. Estimated relationship between bank cost efficiency and deposit-to-total assets.
This figure shows the estimated bank cost efficiency coefficients at different levels of the main variable of interest (DEP TA). The blue solid line represents the marginal effects, while the grey shaded area represents the confidence interval at the 95% level. The horizontal red solid line indicates whether the estimated bank cost efficiency coefficient is positive or negative.

Table 7
Results using an alternative dependent variable.
This table shows the results of the baseline specification performed on the bank-level panel dataset. Cost- to-income is the ratio of operating expenses to operating income. LOANS is the ratio of gross loans to total assets. SIZE is the logarithm of bank total assets. ROA is the ratio of net income to total assets. TOTCAP is the total capital ratio. INT_OP is the ratio of interest income to operating income. LLP is the ratio of loan loss provisions to net interest income. Loan_GR is y-o-y gross loan growth. Zscore is the (ROA plus E/TA)-to-standard deviation of ROA at the country level. INFLATION is the annual growth rate of the Consumer Price Index (CPI). GDP_g is the annual growth in gross domestic product (GDP). Robust standard errors are clustered at the bank-level. *, **, *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

VARIABLES	(1) cost-to-income	(2) cost-to-income	(3) cost-to-income
High-deposits*Post	-0.7979	-2.4752***	-2.0598***
	(0.5237)	(0.5779)	(0.6121)
L.LOANS		-0.0571	-0.0457
		(0.0452)	(0.0461)
L.SIZE		-4.2754**	-3.9376**
		(1.7963)	(1.7645)
L.ROA		-2.1911***	-2.4182***
		(0.7716)	(0.7899)
L.TOTCAP		0.1727***	0.1724***
		(0.0634)	(0.0634)
L.INT_OP		-3.9124	-3.9384
		(3.0401)	(3.081)
L.LLP		0.0095	0.0143
		(0.0134)	(0.0132)
L.Zscore		-4.0762**	-3.8468*
		(2.0757)	(2.0904)
LOAN_GR		-0.1534	-0.1205
		(0.4892)	(0.4883)
L.INFLATION			0.6251*
			(0.3577)
L.GDP_g			0.5837**
			(0.2827)
Observations	8309	6508	6508
R-squared	0.0366	0.0893	0.0959
Number of id	1058	1018	1,018
Bank Fe	Yes	Yes	Yes
Time Fe	Yes	Yes	Yes
Cluster	Bank	Bank	Bank

response to negative interest rates represents a favourable ”side effect” with the potential to benefit the overall banking sector and financial stability.

Disclaimer: The views expressed are those of the authors and do not necessarily reflect the official views of the ECB or the Eurosystem.

CRediT authorship contribution statement

Giuseppe Avignone: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Claudia Girardone:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Cosimo Pancaro:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Conceptualization. **Livia Pancotto:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Alessio Reghezza:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A
Correlation Matrix.
This table represents the correlation matrix for the variables included in the baseline regression model. Correlations that are statistically significant at least at the 5% level are reported in bold. The number on the horizontal axis indicates the variables on the vertical axis. Each horizontal number matches the variable's position in the vertical.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) LOAN		**0.08**	**−0.07**	**−0.36**	**0.15**	**0.02**	**0.07**	−0.02	**−0.10**	**−0.05**
(2) SIZE	**0.08**		**−0.03**	**−0.18**	**0.30**	**0.06**	**−0.08**	**−0.31**	**−0.20**	**0.10**
(3) ROA	**−0.07**	**−0.03**		**0.13**	**−0.16**	**−0.18**	**0.07**	**0.30**	**0.04**	**0.09**
(4) TOTCAP	**−0.36**	**−0.18**	**0.13**		**−0.19**	**−0.12**	**−0.07**	**0.49**	0.01	**0.04**
(5) INT_OP	**0.15**	**0.30**	**−0.16**	**−0.19**		**−0.05**	**−0.10**	**−0.19**	**0.02**	**−0.11**
(6) LLP	**0.02**	**0.06**	**−0.18**	**−0.12**	**−0.05**		**−0.14**	**−0.02**	**−0.25**	**−0.28**
(7) Loan_GR	**0.07**	**−0.08**	**0.07**	**−0.07**	**−0.10**	**−0.14**		**−0.04**	**−0.02**	**0.03**
(8) Zscore	−0.02	**−0.31**	**0.30**	**0.49**	**−0.19**	**−0.02**	**−0.04**		**−0.05**	**−0.04**
(9) INFLATION	**−0.10**	**−0.20**	**0.04**	0.01	**0.02**	**−0.25**	**−0.02**	**−0.05**		**0.15**
(10) GDP_g	**−0.05**	**0.10**	**0.09**	**0.04**	**−0.11**	**−0.28**	**0.03**	**−0.04**	**0.15**	

Notes: LOANS is the ratio of gross loans to total assets. SIZE is the logarithm of a bank total assets. ROA is the ratio of net income to total assets. TOTCAP is the total capital ratio. INT_OP is the ratio of interest income to operating income. LLP is the ratio of loan loss provisions to net interest income. Loan_GR is y-o-y gross loan growth. Zscore is the (ROA plus E/TA)-to-standard deviation of ROA at the country level. INFLATION is the annual growth rate of the Consumer Price Index (CPI). GDP_g is the annual growth in gross domestic product (GDP).

Table B
Number of banks by country and specialisation.

	N.Banks	BHCs	Commercial	Cooperative	Savings
Austria	178	2	15	144	17
Belgium	17	1	12	1	3
Cyprus	4	0	4	0	0
Germany	375	6	21	226	122
Estonia	2	0	2	0	0
Finland	6	0	4	2	0
France	134	5	66	50	13
Greece	7	1	5	1	0
Ireland	6	1	5	0	0
Italy	308	5	47	245	11
Luxembourg	30	1	25	2	2
Malta	5	1	4	0	0
Netherlands	21	6	14	1	0
Portugal	8	2	5	1	0
Slovenia	5	0	3	1	1
Slovakia	8	0	7	0	1
Spain	16	0	12	1	3
Total	1,130	31	251	675	173

Table C
Variables, labels, definitions and sources.

Variable	Label	Definition	Source
Dependent variables			
Cost efficiency	Costeff	The estimated cost efficiency scores based on the Stochastic Frontier Analysis	Authors' calculation
Cost Efficiency	Cost-to-income	The ratio of operating expenses to operating income	Moody's BankFocus & SNL Financial
Variables of interest			
Treated	High-deposit banks	A dummy variable equal to 1 if a bank has a deposit-to-total assets ratio in 2013 above the median, 0 otherwise	Authors' calculation
Post	Post	A dummy variable equal to 1 after the in- troduction of NIRP, 0 otherwise	Authors' calculation

(*continued on next page*)

Table C (*continued*)

Variable	Label	Definition	Source
Treatment	NIRP-effect	The interaction between the dummy Treated and the dummy Post	Authors' calculation
Funding structure	DEP_TA	The ratio of deposits to total assets	Moody's BankFocus & SNL Financial
Asset structure	LOAN	The ratio of gross loans to total assets	Moody's BankFocus & SNL Financial
Bank size	SIZE	The logarithm of bank total assets	Moody's BankFocus & SNL Financial
Profitability	ROA	The ratio of net income to total assets	Moody's BankFocus & SNL Financial
Capitalisation	TOTCAP	The total regulatory capital ratio (TIER1 + TIER2)	Moody's BankFocus & SNL Financial
Business model	INT_OP	The ratio of interest income to operating income	Moody's BankFocus & SNL Financial
Asset quality	LLP	The ratio of loan loss provisions to net interest income	Moody's BankFocus & SNL Financial
Loan growth	Loan_GR	The growth rate of gross loans	Moody's BankFocus & SNL Financial
Z-score	Zscore	Sum of ROA plus the ratio of equity-to-total assets, divided by the standard deviation of ROA at country level	Moody's BankFocus & SNL Financial
Country control variables			
Inflation	INFLATION	The annual growth rate of the Consumer Price Index (CPI)	World Bank
Economic growth	GDP_g	The annual growth rate of gross domestic product	World Bank
Market competition	Lerner Index	The difference between output prices and marginal costs (relative to prices)	World Bank

Table D
Controlling for the heterogeneous impact of NIRP on covariates.
This table shows the results of the baseline specification performed on the bank-level panel dataset where each bank-specific characteristic is interacted with the dummy *Post*. Costeff is the estimated cost efficiency score. High-deposits is a dummy variable that takes the value 1 if in 2013 (i.e. before NIRP), the average ratio of deposits to total assets of bank i located in a NIRP-affected country j was above the median, and 0 otherwise. Post is a dummy variable that assumes the value 1 after the introduction of NIRP, and 0 otherwise. LOANS is the ratio of gross loans to total assets. SIZE is the logarithm of bank total assets. ROA is the ratio of net income to total assets. TOTCAP is the total capital ratio. INT_OP is the ratio of interest income to operating income. LLP is the ratio of loan loss provisions to net interest income. Loan_GR is y-o-y gross loan growth. Zscore is the (ROA plus E/TA)-to-standard deviation of ROA at country level. INFLATION is the growth rate of the Consumer Price Index (CPI). GDP_g is the annual growth in gross domestic product (GDP). Robust standard errors are clustered at bank-level. *, **, *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

VARIABLES	(1) costeff	(2) costeff	(3) costeff
High-deposits*Post	0.0184***	0.0097**	0.0084*
	(0.0041)	(0.0042)	(0.0043)
L.LOANS		0.0005	0.0004
		(0.0003)	(0.0003)
L.LOANS*Post		−0.0000	−0.0000
		(0.0002)	(0.0002)
L.SIZE		.0505**	0.0500***
		(0.0154)	(0.0153)
L.SIZE*Post		−0.0013	−0.0013
		(0.0011)	(0.0011)
L.ROA		−0.0005	0.0002
		(0.0044)	(0.0043)
L.ROA*Post		−0.0053	−0.0052
		(0.0058)	(0.0059)
L.TOTCAP		0.0010*	0.0010**
		(0.0005)	(0.0005)
L.TOTCAP*Post		0.0011**	−0.0011**
		(0.0004)	(0.0004)
L.INT_OP		0.0382*	−0.0376**
		(0.0181)	(0.0183)
L.INT_OP*Post		.0444**	0.0450***
		(0.0107)	(0.0107)
L.LLP		.0002**	0.0002***
		(0.0001)	(0.0001)
L.LLP*Post		0.0004**	−0.0004***
		(0.0001)	(0.0001)

(*continued on next page*)

Table D (*continued*)

VARIABLES	(1) costeff	(2) costeff	(3) costeff
L.Zscore		0.0278**	0.0277**
		(0.0124)	(0.0124)
L.Zscore*Post		0.0102	0.0094
		(0.0075)	(0.0075)
Loan_GR		0.0493*	0.0491*
		(0.0268)	(0.0267)
Loan GR*Post		−0.0412	−0.0411
		(0.0271)	(0.0271)
L.INFLATION			−0.0004
			(0.0020)
L.GDP_g			−0.0023**
			(0.0010)
Observations	8455	6760	6760
R-squared	0.0146	0.0971	0.0994
Number of id	1,107	1,053	1,053
Bank Fe	Yes	Yes	Yes
Time Fe	Yes	Yes	Yes
Cluster	Bank	Bank	Bank

Table E

Alternative continuous variable computation.

This table shows the results of the baseline specification performed on the bank-level panel dataset. Costeff is the estimated cost efficiency score. High-deposits is the average ratio of deposits to total assets of bank i located in a NIRP-affected country j in the year 2013. Post is a dummy variable that assumes the value 1 after the introduction of NIRP, and 0 otherwise. LOANS is the ratio of gross loans to total assets. SIZE is the logarithm of bank total assets. ROA is the ratio of net income to total assets. TOTCAP is the total capital ratio. INT_OP is the ratio of interest income to operating income. LLP is the ratio of loan loss provisions to net interest income. Loan_GR is y-o-y gross loan growth. Zscore is the (ROA plus E/TA)-to-standard deviation of ROA at country level. INFLATION is the growth rate of the Consumer Price Index (CPI). GDP_g is the annual growth in gross domestic product (GDP). Robust standard errors are clustered at bank-level. *, **, *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

VARIABLES	(1) costeff	(2) costeff	(3) costeff
High-deposits (contin.treatment 2013)*Post	0.0010***	0.0008***	0.0008***
	(0.0001)	(0.0001)	(0.0001)
L.LOANS		0.0002	0.0001
		(0.0003)	(0.0003)
L.SIZE		0.0343**	0.0334**
		(0.0161)	(0.016)
L.ROA		−0.0055	-0.0042
		(0.0036)	(0.0035)
L.TOTCAP		0.0003	0.0003
		(0.0004)	(0.0004)
L.INT_OP		-0.014	−0.0138
		(0.0155)	(0.0157)
L.LLP		0.0000	0.0000
		(0.0001)	(0.0001)
L.Zscore		0.0370***	0.0358***
		(0.0133)	(0.0133)
Loan_GR		0.0081**	0.0080**
		(0.0034)	(0.0034)
L.INFLATION			−0.0001
			(0.0021)
L.GDP_g			−0.0027***
			(0.001)
Observations	8,358	6724	6724
R-squared	0.0449	0.0788	0.0824
Number of id	1,094	1,047	1,047
Bank Fe	Yes	Yes	Yes
Time Fe	Yes	Yes	Yes
Cluster	Bank	Bank	Bank

Data availability

The authors do not have permission to share data.

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